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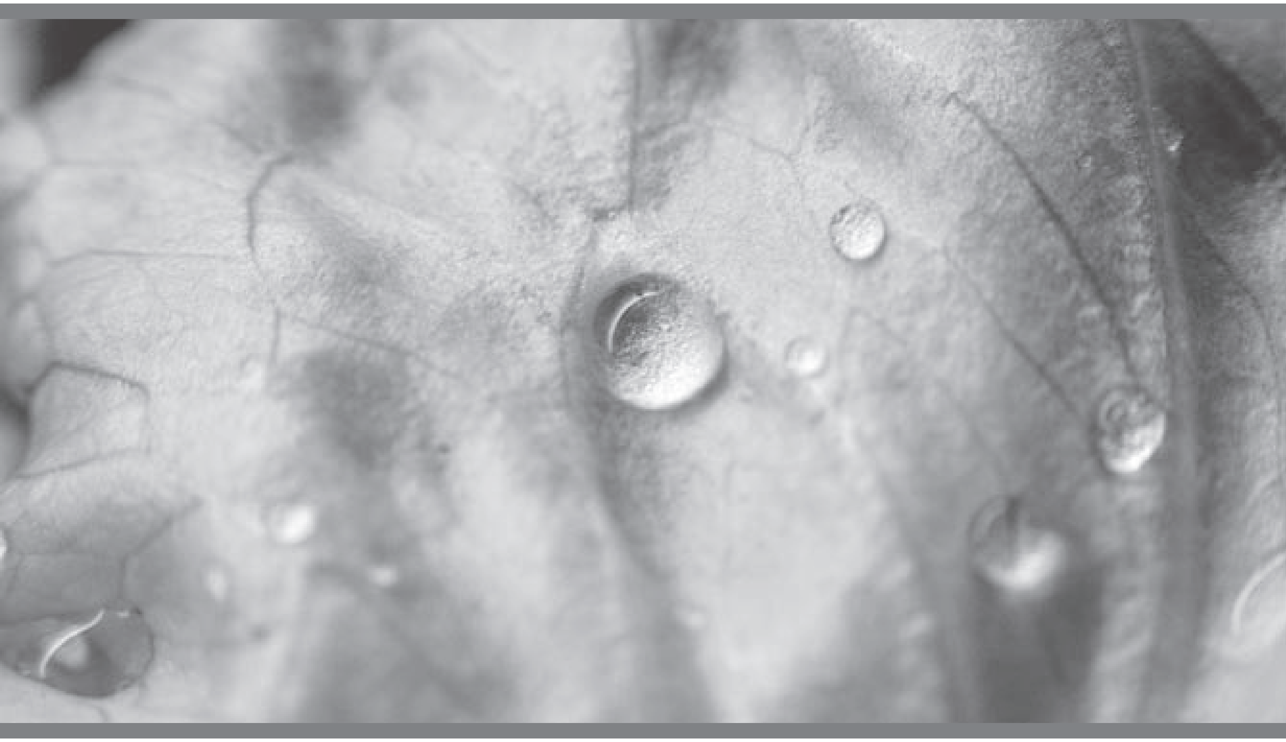

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Wrocław 2016

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Łamanie i projekt okładki
Paweł Wójcik

Monografie CCII

ISSN 2083–5531
ISBN 978-83-7717-253-7

WYDAWNICTWO UNIWERSYTETU PRZYRODNICZEGO WE WROCŁAWIU
Redaktor Naczelny – prof. dr hab. inż. Andrzej Kotecki
ul. Sopocka 23, 50–344 Wrocław, tel. 71 328 12 77
e-mail: wyd@up.wroc.pl

Nakład 100 + 17 egz. Ark. wyd. 11,3 Ark. druk. 10,0
Druk i oprawa: Drukarnia PRINT Sp. j.
Z. Przyborowski, H. Ambroży
ul. Wykładowa 62, 51–520 Wrocław

Spis treści

1. Introduction

Water is a factor that is indispensable, in varying amounts, for all organisms living on Earth. The significance of that factor is clearly observable in the estimation of the growth and development of plants – both wild growing and crops. The modern industry and agriculture have high requirements also as concerns the quality of water that they use. The growing population and the improving standard of living also cause an increased consumption of water. In many cases these factors have cumulative effects and enforce rational use of the limited water resources, which applies also to the resources of soil water. For this reason studies are conducted with the aim of their indirect estimation [Dąbrowska-Zielińska 1991, Romano and Palladino 2002, Stoffregen et al. 2002]. This situation creates the need for searching for possibilities of water acquisition and use from ever new sources. The problems related with the above are also amplified by the process of climate change [Lorenc 2005, Ziernicka-Wojtaszek and Zawora 2008] and the climatic anomalies observed over the recent years. Analysis of the seasonal structure of anomalous years, due to the two most frequently used meteorological factors – air temperature and precipitation, permitted to indicate those years which were particularly unfavourable for agricultural production in the second half of the 20th century [Żmudzka 2004]. Those occurrences put special emphasis on the fact of the necessity of rational use of water [Stone et al. 2010, Supit et al. 2010]. Rational management of water resources is possible in the situation of fairly precise recognition of the water requirements of particular groups of plants. Numerous studies conducted all over the world demonstrated clearly the fact of losses of considerable amounts of water as a result of e.g. non-productive field evaporation. The various levels of ground water affect soil moisture, plant yields, and thus also the value of evaporation [Chen, Hu 2004, Kahlown et al. 2005]. For those reasons the knowledge of evaporation of plants during their vegetation permits the identification of periods of increased demand for water and periods in which limited availability of water contributes to a significant reduction of yields. Attention is also paid to the factors of temperature and exposition [Weng and Ueng 1997]. The search for new sources of energy have also been directed onto plants which can be used as biomass for its generation. Their cultivation permits combining the possibilities of producing considerable amounts of biomass for combustion or for biogas. For this reason the world priorities related with the search for renewable sources of energy have directed the attention of researches to biomass. The legal foundations in this respect are provided in the Strategy of Development of Renewable Energy adopted by the Polish Parliament in 2001, assuming that the share of energy from renewable sources, including biomass, will attain the level of 7.5% already in 2010. The realization of that Strategy is to be supported by the Regulation of the Minister for the Economy, Labour and Social Policy which imposes an obligation of purchasing energy produced in that manner. The group of plants used for that purpose is commonly referred to as energy crops. Measures applied to acquire considerable amounts of biomass include, among other things, additional fertilisation, e.g. with the use of sewage sludge that constitutes one of the form of communal wastes and that can be used as an additional fertiliser for plants, with simultaneous possibility of utilisation of burdensome wastes [Kalembasa et al. 2006]. Energy crops are also a significant environment permitting the elimination of notable amounts of carbon dioxide [Heaton et al. 2004].

Biomass is a raw material for the production of solid, liquid and gaseous carriers of energy. It is especially beneficial from the viewpoint of environmental protection, and its greatest advantage is the practically zero balance of carbon dioxide, lower emission of sulphur and nitrogen oxides compared to fossil fuels, and greater reliability as a source of energy compared to other renewable sources such as wind or solar energy.

These problems make it a necessity to acquire knowledge about the environmental processes which determine high productivity of those crop plants. One of those processes is evapotranspiration determined by the kind of plants in cultivation, availability of water, and the weather conditions during the vegetation period. For many years now research has been conducted in the world on the modelling of the process of evapotranspiration and on its effect on the production of plant biomass. These premises have been used by the authors of this work to undertake an attempt at estimation of water management by a selected group of energy crops under conditions of its diversified availability during the vegetation period.

Research financed from Polish budget funds for science in the years 2010–2013 as research project No. N N305 383539.

2. Symbols used in the paper

$\alpha, \beta, \gamma, \theta, \delta$ – model parameters
Bw – relative error
cp – free access to ground waters
cw – limited access to ground waters (energy crop plants in soil evaporimeters)
D – consecutive day of the year
Ep – reference evapotranspiration (ET_0) calculated with the application EVAPO, acc. to the formula – “FAO–Penman–Monteith” [mm]
ETR – evapotranspiration [mm]
ETRw – evapotranspiration of basket willow (*Salix viminalis*) during vegetation [mm]
Ew – evaporation from open water surface measured with evaporimeter EWP 992 [mm]
ETR_i – actual evapotranspiration on i-th day of vegetation [mm] from model WSMT
E_{0i} – evaporation from open water surface on i-th day of vegetation [mm]
ETRŚ – sums of evapotranspiration of Virginia mallow in periods between biometric measurements
ETRŚśr – diurnal evapotranspiration of Virginia mallow (*Sida hermafrodita* Rusby) on consecutive days of a given year averaged for all evaporimeters [mm]
ETRŚśr s – cumulative diurnal sums of averaged sums of evapotranspiration of Virginia mallow from the start of study periods in the particular years [mm]
EWP 992 – type of evaporimeter used for measurements of evaporation from open water surface – measurement accuracy to 0.1 mm
EVAPO – application permitting calculations, with the “FAO–Penman–Monteith” formula, of diurnal values of reference evapotranspiration (ET_0), understood as the value of evaporation from the surface of fully developed lawn growing on soil which ensures optimum vegetation conditions.
Hg and Wg – mean decade levels of groundwater table [cm]
k – mean values of empirical coefficients “k” for the calculation of evapotranspiration of energy crop plants for various time intervals
M – giant Miscanthus grass (*Miscanthus x giganteus*)
Mp – calculated field water consumption under giant miscanthus grass on experimental plot [mm]

Mw – calculated field water consumption under giant miscanthus grass in soil evaporimeter [mm]
m – mass of plants harvested after the end of vegetation [g]
n – n-th day of vegetation
nr ewap – number of soil evaporimeter
obj – c – increase of green matter volume of aboveground part of a single plant [cm^3]
P – sums of atmospheric precipitations [mm]
P_i – value of atmospheric precipitation on i-th day of vegetation [mm]
Penman – cumulated values of diurnal sums of evaporation [mm]
ΔP [%] – deviations of decade sums of precipitations from normal values from the period of 1971–2000
PZW – field water consumption [mm]
R^2 – coefficient of determination
W – basket willow (*Salix viminalis*)
WG – depth of groundwater table [cm]
Wild – cumulated values of diurnal sums of index evaporation measured with EWP 992 [mm]
Wp – calculated field water consumption under basket willow on experimental plot [mm]
Ww – calculated field water consumption under basket willow in soil evaporimeter [mm]
WSMT – model name formed from the first letters of energy crops chosen for the study
Ś – Virginia mallow (*Sida hermafrodita* Rusby)
Śp – calculated field water consumption under Virginia mallow on experimental plot [mm]
Św – calculated field water consumption under Virginia mallow in soil evaporimeter [mm]
T – Jerusalem artichoke (*Helianthus tuberosus*)
TDR – method of soil moisture measurement with the use of Time Domain Reflectometry
Tp – calculated field water consumption under Jerusalem artichoke on experimental plot [mm]
Tw – calculated field water consumption under Jerusalem artichoke in soil evaporimeter [mm]
tp – values of air temperature [°C]
tp sum – cumulated sums of air temperature for various time intervals [°C]

3. Review of literature

Biomass is defined in EU as well as in Polish documents. In the approach of the EU laws, biomass is the biodegradable part of products, wastes or biological residues from agriculture (including plant and animal substances), forestry and the related branches of industry, including fishery and acquaculture, and the biodegradable part of industrial and municipal wastes [Dyrektywa Parlamentu Europejskiego i Rady 2009/28/WE]. It is also included in the definition of bioliquids, i.e. the so-called secondary fuels. Those are liquid fuels used for energy generation purposes, other than those used in transport, including the generation of electric power, as well as heat and cooling, produced from biomass. Whereas, the Regulation of the European Parliament and EC Council No. 1099/2008 defines solid biomass as organic non-fossil substances of biological origin that can be used as fuels for the production of heat energy or electric power, including wood, crop plants, biodegradable solid wastes, etc. At the scale of Poland, the concept of biomass is defined by the Act of 25th August, 2006, on biofuels and liquid biocomponents [Dz.U. 2006, Nr 169, poz. 1199], according to which biomass is solid or liquid substances of plant or animal origin, subject to biodegradation, from products, wastes and residues from agricultural and forestry production, from industry processing their products, as well as parts of other biodegradable wastes, agricultural raw materials in particular. Definitions of biomass are given also in the Act of 27th April, 2001, on wastes [Dz.U. 2007, Nr 39, poz. 251] and the Rozporządzenie Ministra Gospodarki z dn. 14 sierpnia 2008 r. [Dz.U. z 28 sierpnia 2008 r. Nr 156, poz. 969 ze zm.].

Compared to other renewable sources, in Poland biomass is used most extensively in the energy sector: in the sector of electric power generation 60% of energy produced comes from biomass, in the sector of heat and refrigeration – ca. 95%, while in transport – ca. 100% is accounted for by 1st generation fuels, i.e. bioethanol and biodiesel.

Oils from various plants are a significant material for the production of biocomponents of solid fuels, the highest yield of lipids per unit of cultivation area in our climate zone being obtained from winter rape [Budzyński and Bielski 2004, Jankowski and Budzyński 2003, 2004, Podkówka 2002]. Whereas, the production of bioalcohol is conducted with the use of such raw materials as e.g. cereals, among which maize is the most effective. In this case it is also possible to use potatoes of the lowest quality, or Jerusalem artichoke which, however, is not used in practice for the production of alcohol. The highest productivity per unit of cultivation area is characteristic of sugar beet whose waste product, molasses, constitutes a significant source of bioethanol [Budzyński and Bielski 2004, Kupczyk and Ekielski 2002, Lipski 2003, Łabętowicz et al. 1999, Ostrowska and Cieśliński 2003, Pimentel and Patzek 2005].

The production of biomass in the form of solid fuel is based primarily on plants referred to as the energy crops which include arborescent plants with fast rotation, i.e. willow, poplar, aspen or eucalyptus, fast-growing perennial grasses, i.e. reed canarygrass or miscanthus grass, yielding every year, annual shrubs and perennials, annual crop plants, i.e. cereals, maize, rapeseed, sugar cane, sorghum. Their common characteristic is the accumulation of suitable amounts of oils or hydrocarbons used for the production of energy carriers. Studies on the suitability of those plants for the production of energy carriers are conducted in various aspects [e.g. Budzyński and Bielski 2004, Borkowska and Molas 2012, Faber et al. 2007, Głowacka 2011, Jeżowski 2001, Kieć et al. 2011, Kim and Kim 2014, Kościk et al. 2003, 2004, Kotecki et al. 2010, Rayburn et al. 2009]. Research is also undertaken on the possibility of utilising algae as a source of biomass. As reported by Kozieł and Włodarczyk [2011], within the nearest time perspective there will be an increase of the production of algae due to the fact of small area of cultivation compared to other raw materials, and the broad spectrum of possibilities of utilisation of algal biomass.

Directive 2009/28/EC is enumerated among the legal acts created for the realization of the "20–20–20" package which is aimed at ensuring the realization of assumptions concerning the counteracting of climate changes. It means that by the year 2020 three objectives will have been realized in 20%: reduction of carbon dioxide emissions, energy saving, and the target share of energy from renewable sources. In the case of Poland, the share of energy from renewable sources should attain the level of 15% by the year 2020 [Szczukowski et al. 2012]. According to the Energy Policy of Poland, the development of renewable energy production permits greater diversification of sources of supply and, as opposed to fossil fuels, allows the development of scattered energy production. The utilisation of local raw materials ensures, to an extent, local energy security and reduces energy transport costs. In relation to the above, high expectations are placed on the acquisition of energy from biomass. Apart from the unquestionable advantages of biomass as an energy carrier, that form of energy acquisition is also characterised by certain negative aspects. The relatively low fuel value of biomass, compared to conventional fuels, means the need of storing twice as much of biomass as of e.g. coal. Moreover, the seasonal nature of biomass enforces the necessity of purchasing greater amounts in the summer. Some problems may also arise from the scattered suppliers of the fuel (from several to several dozen), which may create logistics problems in the supply system of that energy carrier. In addition, the cultivation and harvest of those plants requires energy inputs (emission of CO_2 during the combustion of fossil fuels by machinery), and in intensive cultivation they require fertilisers or chemical protection (the production of such agents requires also energy inputs), which in a way is contrary to the common conviction concerning their zero CO_2 balance [Dubert et al. 2010].

The issue of the potential of biomass on the scale of the world, Europe and Poland is addressed in studies by such authors as e.g. van Dam et al. [2007], Ericsson et al. [2006], Hoogwijk et al. [2005], Krasuska and Rosenqvist [2012], Tuck et al. [2006], de Wit and Faaij [2010], Hellmann and Verburg [2011], or Voivontas et al. [2001]. Those studies differ in their objectives, approach and results. The projected increase of cultivation of energy crops in Europe will require large areas, which obviously may cause the appearance of symptoms of competition between the production of biofuels and crops grown for food. Therefore the subject-matter of energy crops in the context of cultivation area is addressed in many studies, e.g. by Hellmann and Verburg [2011], Strengers et al. [2004], De La Torre Ugarte and Ray [2000] and Verburg et al. [2006].

Poland has a high biomass market potential, but the sector of energy crop cultivation is only at the start of development. High hopes are placed on the establishment of multi-year plantations of energy crops. This creates the necessity of determining the demand and the possibilities of energy crops cultivation in the territory of Poland. It concerns the utilisation of agricultural space for that production, taking into account the competition of various crops in terms of their share of the agricultural space. That space is shrinking due to the fact that areas surrounding urban agglomerations are set apart for future housing construction. In view of the legal constraints, both EU and Polish, concerning the utilisation of biomass for energy production, it is necessary to develop predictions of trends in the structure of utilisation of the agricultural space of Poland within the perspective of at least the year 2020. According to a study by Stuczyński et al. [2008], with the current policy concerning energy crops and the share of biocomponents in biofuels there is no threat of decrease of the area of cultivation of conventional crops, i.e. cereals. There may even be certain positive consequences in the form reducing the area of fallows and idle soils, which will counteract the loss of agricultural character of many regions.

It is estimated that by the year 2020 in Poland the cultivation of energy crops can be conducted on from 1 to 4.3 million hectares of arable lands [Szczukowski et al. 2012]. According to Faber [2008], multi-year plantations of energy crops are characterised by large annual increments, hence their notably higher water requirements. According to Hall [2003], water consumption by willow varies from 550 to 650 mm, and that of miscanthus grass from 510 to 600 mm, which may enforce the location of such plantations on soils with high levels of groundwater table (< 2 m). What is more, those plants are characterised by a high interception, low surface runoff, and consequently negligible water infiltration into the depth of the soil profile. Such plantations can have enormous hydrological effects due to reduced ground waters supply from precipitation. However, as indicated by Berneds [2002], ligno-cellulosic plants are characterised by notably higher effectiveness in the utilisation of water compared to conventional crops (10–95 kg d.m.$\cdot$h$^{-1}\cdot$mm^{-1} ET). Studies by Kowalik and Scalenghe [2009] indicate that the water requirements of plantations aimed at the production of biomass are 2–3-fold lower in Poland compared to South European countries.

With the above in view, studies are conducted on the most rational and balanced use of soils for the cultivation of those plants. Ostrowski et al. [2009] proposed a division of soils with regard to the water requirements of energy crops for the purpose of classification and estimation of suitability for energy crops cultivation, on the example of the Świętokrzyskie Province. Those authors classified in Group 1 soils suitable for the cultivation of plants preferring moist soils and at the same time sensitive to precipitation deficit, i.e. willow (*Salix viminalis* L.), Sakhalin knotweed (*Reynoutria sachalinensis*) or reed canarygrass (*Phalaris arundinacea* L.). Group 2 included soils suitable for the cultivation of plants tolerant of varied moisture and characterised by low sensitivity of precipitation deficit, i.e.

prairie cordgrass (*Spartina pectinata*) or giant *Miscanthus* grass (*Miscanthus sinensin gigantea*). Whereas, Group 3 comprised soils suitable for the cultivation of plants tolerant of low soil moisture and little sensitive to precipitation deficit, e.g. Virginia mallow (*Sida hermaphrodita* (L.) Rusby) or Jerusalem artichoke (*Helianthus tuberosus* L.).

Stelmach et al. [2008] undertook an estimation of the optimum utilisation of the capabilities of arable soils under energy crops plantations in the Ciechanów District, without losses in other crops, to adapt the scale of production to the needs of a given region. Such an approach was aimed at solving the problem of surplus biomass production in the region, the transport of which over any greater distances would be uneconomical.

The most suitable energy crops are those which are characterised by efficient conversion of solar radiation energy into biomass, and by a high content of dry matter. At the same time, such plants should be characterised by sparse water management, high resistance to diseases and to unfavourable environmental conditions. Another important aspect is the possibility of mechanisation of many operations involved in the establishment, operation and liquidation of the plantation. Hence the importance of the energy balance, as the relation between the total costs of plant production and the amount of energy acquired in the process of combustion [Kowalik et al. 2009, Szczukowski et al. 2002]. This subject-matter has been addressed in their studies by e.g. Ericsson et al. [2006], Hryniewicz and Grzybek [2010], Kwaśniewski [2006], Piskier [2010] or Simon et al. [2009]. One of the solutions is the development of models of energy crops cultivation for correct management of their production [e.g. Bal et al. 2005, Grzybek 2010, Piskier 2010, Węgrzyn and Zając 2008].

Theoretically the climatic conditions of Poland are favourable for the cultivation of many species of energy crops. The most common in cultivation are such plants as basket willow (*Salix viminalis*), giant *Miscanthus* grass (*Miscanthus x giganteus*), Virginia mallow (*Sida hermafrodita* Rusby), reed canarygrass (*Phalaris arundinacea* L.) or Jerusalem artichoke (*Helianthus tuberosus*). Soils used for their cultivation are mainly lower quality, fallowed or idle, as well as contaminated soils. In the case of the latter ones the cultivation of those plants may be of special importance, as the plantations can be used as a phytoremdiation method of reclamation [e.g. Jansen et al. 2009, Kabała et al. 2010, Mleczek et al. 2009, Pidlisnyuk et al. 2014, Szakova et al. 2004, Weih and Nordh 2002]. Plants used for that purpose should be characterised by a high tolerance to toxic substances, a high capacity for the uptake and accumulation of substances in their biomass and, equally important, produce a high yield of biomass. In addition, the cultivation of those plants of poor quality soils provides the opportunity of simultaneous utilisation of sewage sludge for their fertilisation. Very often sewage sludge, due to a high content of heavy metals, has limited application because of the possibility of contamination of soils and plants, hence ongoing research on the possibility of its use for the amendment of non-food cultivations, especially energy crops and industrial plants [e.g. Augustynowicz et al. 2010, Kalembasa et al. 2009, Liphadzi et al. 2003, Kozak et al. 2006, Niemiec et al. 2007].

The best conditions for the cultivation of energy crops are characteristic of the southern and northern regions of Poland. In the central belt of Poland (with precipitation sum of the summer half-year not exceeding 300 mm) such plantations should be located due to decreased yields, especially inyears with large precipitation deficits [Kuś and Matyka 2010]. Such plantation should not be established also on very good soils that should be used solely for the production of food and fodders. Also excluded from such use are protected areas, mountain regions situated at elevations higher than 350 m a.s.l., as well as meliorated fields and those with slope greater than 12°, due to notable difficulties in mechanised harvest of biomass.

Since under the conditions of Poland high productivity is achieved for basket willow and Virginia mallow, those plants have been the object of numerous studies, e.g. those by Borkowska and Styk [2006], Borkowska and Molas [2012, 2013], Faber et al. [2007], or Jurczyk et al. [2010]. In Poland the climatic conditions are suitable for the cultivation of basket willow practically over the entire territory of the country, but precipitation deficits occurring during the critical period for that plant (from June to August) and the accompanying high temperatures are factors inhibiting large increments of biomass. Whereas, in spite of the common conviction about the hydrophilicity of willow, long-lasting flooding of cultivation areas lead to the decay of plantations situated in such areas. Likewise, in Poland there are suitable conditions for the cultivation of Virginia mallow which does not have any high soil and climate requirements. In this case, however, the necessary condition is sufficient soil moisture. Giant *Miscanthus* grass also enjoys a high popularity, and it has been the object of research by e.g. Borkowska and Molas [2013], Faber et al. [2007], Jeżowski et al. [2009], Matyka and Kuś [2011], and Szempliński and Dubis [2011]. It is a thermophilic plant, with C4 photosynthesis mechanism, which is conducive to low water consumption per unit of dry matter produced. However, during the vegetation period its water requirements amount from 500 to 600 mm of precipitation. Miscanthus is a thermophilic plant (the optimum temperature for its growth is 28–32°C), but the sums of temperatures under our conditions permit the obtainment of satisfactory levels of yields. In the first year of cultivation, low temperatures during winter can be a threat to the plant. High hopes are placed on the use of Jerusalem artichoke, hence studies on the possibility of its yielding under various conditions [e.g. Góral 1998, Klimont 2012, Prośba-Białczyk 2007]. In our climatic zone that plant is characterised by the highest potential of biomass production. Compared to other plants, its use for energy purposes includes both the tubers (production of alcohol or biogas) and the aboveground parts – for direct combustion or for the production of pellets and briquettes. It is also characterised by low habitat requirements and the possibility of self-renovation [Szczukowski et al. 2012] that can often be a problem in the maintenance of a plantation in good condition. Detailed characterisation of the above energy crops is presented further on in the text of the paper.

The observed climate change and the increasingly frequent anomalies concerning two meteorological factors – air temperature and precipitations – indicate the necessity of rational water management [Stone et al. 2010, Supit et al. 2010, Ziernicka-Wojtaszek and Zawora 2008, Żmudzka 2004]. Such an approach is only possibly when we have precise knowledge about the water requirements of particular groups of plants. At the same time, numerous studies conducted both in Polish centres and abroad clearly indicate the fact of considerable losses of water as a result of non-productive area evaporation. Therefore the knowledge of evapotranspiration of various plant groups during their vegetation permits the recognition of their intensified water requirements and of periods during which reduced availability of water causes a notable reduction of their yielding. This problem is very important also in the case of energy crops, where the amount of biomass acquired from a plantation is determined primarily by the water factor, the soil and fertilisation conditions being of lower importance. Without water plants quickly desiccate, terminating their vegetation, and produce small increments [Sławiński 2009]. Under such conditions plantations become economically non-viable. Hence the importance of recognition of evapotranspiration determinants of energy crops, and that is possible only through experimental studies on the process. The determination of the value of actual evapotranspiration, which is the resultant of numerous mutually correlated physical and biological factors, is a fairly difficult task and though that problem has been addressed for a long time, until now it poses many difficulties. The main obstacle is the lack of sufficient data from actual measurements. There care indirect methods of determining its value. They consist in the calculation, with one of numerous methods, of the value of index evaporation or potential evaporation, and then adopting those as the base values for the determination of calculated empirical coefficients [Bac and Rojek 2012, Kędziora 1995].

The intensity and dynamics of evapotranspiration and water balance of soil for various plants has been studied in the past at many research centres in Poland (Bydgoszcz, Poznań, Puławy, Warszawa, Wrocław). A notable amount research results, dating back to the beginning of the nineteen sixties, can be found in numerous publications such as papers, monographs, DSc dissertations, or in conference materials related with that subject matter. The studies were concerned primarily with crop plants, due to the demand for this type of information existing at that time. Comprehensive studies on the process of evapotranspiration of various crop plants and on the effect of weather conditions on that process, and on the estimation of their potential production capacity, have been and are still being conducted, since the beginning of the 1960's, at the Agro- and Hydrometeorological Observatory of the University of Environmental and Life Sciences in Wrocław, where also the experiment related with the subject of this monograph is being conducted.

The study of the process of evapotranspiration under field conditions, or of the field water consumption, does not provide fully credible information on the variation of water resources as a result of their exhaustion by the root system of plants. Then problem can be solved by means of precision experiments conducted with the use of lysimeters or evaporimeters. Such an approach was applied in their research by e.g. Bac and Pasierski [1989], Yang et al. [2013], Jackson and Wallach [1999], Kahlown et al. [2005], Liu et al. [2002], or Stoffregen et al. [2002]. Studies of that kind are also conducted for selected species of energy crops. Due to their popularity, the studies are concerned mainly with various willow varieties [Białowiec et al. 2007, Martin and Stephens 2008] or *Miscanthus* [Triana et al. 2014]. Since lysimetric experiments are rather laborious, difficult to conduct and expensive because of the specialist apparatus required, models are developed for the estimation of the value of evapotranspiration based e.g. on the values of evaporation determined with the method of Penmann-Monteith [Gardiol et al. 2003, Lecina et al. 2003, Loos et al. 2007, Zhou and Zhou 2009]. Also existing models are used for that purpose, permitting the estimation of evapotranspiration of selected plants, e.g. ALMANAC, ECOWAT, the model of Shyttleworth and Wallace (the SW model for short) [Ortega-Farias et al. 2010, Schilling and Kiniry 2007, Spano et al. 2009, Tourula and Heikinheimo 1998]. The above models have also found an application for the estimation of evapotranspiration of energy crops, the existing studies being focused mainly of various willow varieties [Iritz et al. 2001, Irmak et al. 2013, Persson 1995]. The authors of this work proposed the WSMT model for the estimation of evapotranspiration of 4 energy crops: willow, Virginia mallow, giant miscanthus grass and Jerusalem artichoke. The model permits the determination of actual evapotranspiration on the basis of precipitation and evaporation from free water surface [Żyromski et al. 2012a]. The model was developed on the basis of 2-year direct measurements of evapotranspiration of those plants with the use of soil evaporimeters.

Another approach to the estimation of evapotranspiration is the application of the remote sensing technique [Gibson et al. 2013, Sanchez et al. 2008].

From the viewpoint of water requirements of plants and increase of biomass it is also important to have information on the value of transpiration itself, that being regulated autonomously by plants for the purpose of maximisation of the efficiency of photosynthesis, or for the minimisation of water losses. Hence, studies have been conducted for years on the value of transpiration of plants, including energy crops [Brisson et al. 1998, Gazal et al. 2006, Hall et al. 1998, Schaeffer et al. 2000].

For the receivers of biomass it is important to have information on its current amounts on the plantation during the vegetation period. As already mentioned, water availability for plants determines their high productivity, which is reflected primarily in the value of evapotranspiration. Therefore, for years now many research centres are working on the development of mathematic models permitting the estimation of the amount of biomass from energy crops, where the value of evapotranspiration determined directly or described comprehensively by means of various parameters (e.g. meteorological or soil parameters) constitutes the input data for models permitting the estimation of its current amount on the plantation. An extensive review of models for the estimation of the amount of biomass from energy crops is presented in the work by Surrendran Nair et al. [2012]. Generally, the models can be divided into two groups. The first group are empirical models that use data from direct measurements to identify relations between the level of yields of plants and selected climatic and soil factors or cultivation treatments. The second group includes mechanistic models whose operation consists in correlating physiological and morphological features which determine plant growth. This is done using models directly dedicated for energy crops or by adapting existing models of plant yielding. As an example, such models as e.g. EPIC [Williams et al. 1984], ALMANAC [Kiniry et al. 1992], MISCANMOD [Clifton-Brown et al. 2000], MISCANFOR [Hastings et al. 2009], WIMOWAC [Humphries et al. 1995] or Agro-Ibis [Kucharik 2003] are sued for the estimation of the amount of biomass from plantations of giant Miscanthus grass, while biomass yields for willow are estimated by means of e.g. models 3PG or LINPAC [Amichew et al. 2011, Jing et al. 2012, Landsberg et al. 1997, Sannervik et al. 2006]. Those models, in their majority, require input data in the form of good quality data concerning e.g. the dynamics of leaf surface area, phenological phases, meteorological data, i.e. solar radiation intensity, air temperature, sums of precipitation, or data on cultivation treatments applied, that are often hard to acquire. These authors, whose earlier studies dealt with the modelling of yields of various crop plants, e.g. barley, wheat, potato [Szulczewski et al. 2010, 2012, Żyromski et al. 2013], on the basis of results of experiments proposed a novel method for the estimation of the current amount of biomass, developed for energy willow during the period of its vegetation. Several years of research on energy crops and analyses of the results of field experiments permitted the development of a method which is based only on results from simple biometric measurements on plantations of that crop plant. Such measurements can be made by the planters themselves, practically without any financial outlays and any major disturbances on the plantation. Practical verification of the results on independent material will permit the adaptation of the method for other energy crops.

The field experiments concerning the levels of yielding of energy crops indicate their notable variations – from several to several dozen tons of dry matter per 1 ha·year^{-1}. As reported by Szczukowski et al. [2012], on average the yields are estimated at from 8 to 12 tons of dry matter per year, but yields of as much as 20 tons of dry matter per 1 ha per year are also obtained. This level of variation results primarily from the soil-water conditions, hence this is the aspect in which research is being conducted at many research centres [e.g. Borkowska and Molas 2013, Faber et al. 2007, Fischer et al. 2011, Jurczyk et al. 2010, Szempliński and Dubis 2011]. The cause of low yields may be problems with correct preparation of the field, errors in the establishment of a plantation, or incorrect fertilisation.

The literature review does not fully exhaust the subject-matter concerning the cultivation of energy crops. It does indicate, however, that the subject-matter is very much current and prospective, especially in the perspective of complying with the requirements of the cited Directive 2009/28/EC. Hence the extreme importance of precise recognition of the variation of possibilities of the growth and development of energy crops cultivated in Poland. Taking into account their varied access to water is of key importance. The novel approach, proposed in this work, to the modelling of the process of evapotranspiration of such energy crops as basket willow, giant miscanthus grass, Virginia mallow and Jerusalem artichoke may be especially useful for the selection of regions of cultivation within the territory of the country so that the cultivation may be economically viable. The important fact is that the cultivation of those plants in the experiment was conducted with the extensive method. Every enrichment of the cultivation in fertilisers and water contained e.g. in sewage applied on the field may significantly enhance their productivity, as indicated by numerous studies conducted both in Poland and in the world [e.g. Kalembasa et al. 2006, 2008, 2009, Martin and Stephens 2008, Styszko et al. 2008, Himken et al. 1997].

4. Brief characterisation of the selected energy crops

Below is the presentation of a brief characterisation of the energy crops used in the field experiment which is the subject-matter of this monograph. Four energy crops were selected for the study, i.e. basket willow, Virginia mallow, giant miscanthus grass, and Jerusalem artichoke, that are considered to be the most prospective energy crops in Poland, on the one hand because of the favourable conditions for their cultivation, and on the other – due to their high potential of biomass production. Those species represent short-rotation arborescent cultivations, introduced species of grasses with C4 photosynthesis pathway, as well as fast-growing perennials.

4.1. Basket willow (*Salix viminalis* L.)

Genus: osier – *Salix*, belongs to the willow family – *Salicaceae*, occurring in two forms: deciduous trees and shrubs. According to various authors, there are from 300 to over 500 species of that plant in the world, from which 28 species have been identified in Poland.

The most popular species of willow grown on agricultural lands for energy purposes is basket willow *Salix viminalis* L. Wood biomass from field cultivations of basket willow can be acquired in one-, two-, three- or four-year harvest cycles for 20–25 years.

Basket willow is a plant that grows very well in the climatic conditions (temperature-precipitation) prevalent in Poland. The necessary condition for successful cultivation is sufficient level of precipitations, especially in the case of newly established plantations. The weather in the period from June to August has a significant effect, as during that period willow is characterised by the most intensive growth of biomass. Precipitations and moderately high temperature during that period have a favourable effect on biomass yields, while drought may cause a drop of yields by even 50–70%. Apart from precipitation water, moisture accumulated in the soil after the winter is very important for willow, as well as the level of groundwater table (1–1.5 m). Even though willow is a thermophilic species, it does not tolerate areas subject to periodic flooding. Wherever the ground gets flooded and the floodwater stays for periods longer than 2–3 weeks, willow falls out.

Agricultural lands with reaction from slightly acidic to neutral (pH 5.5–7.0) are good habitats for plantations of fast-growing species of willow. Suitable soils are those from the higher soil quality classes, e.g. III a and b, IV a and b, and alluvial soils that can be periodically over-moist, but not waterlogged (usually used as grasslands). On poorer soils, from the lower soil quality classes, fast-growing willow can be cultivated, but under the condition that the soils have a high level of groundwater table or will be irrigated and amended with mineral and organic fertilisers. It is also possible to utilise soils contaminated by the industry, e.g. with heavy metals, on which the cultivation of crop for food is not rational.

In the cultivation of willow it is important to correctly plan the plantation so as to permit full mechanisation of all cultivation operations (planting, fertilisation, care, harvest). The planting material for the establishment of field plantations of energy willow are cuttings with length of 20–25 cm and diameter of over 7 mm.

First of all, for the establishment of willow plantation for energy purposes one should selected cultivars (clones) characterised by the most intensive growth in the first year of the plantation, and a high yield of biomass with a high calorific value. It should also be resistant to yield-limiting factors, i.e. frost, diseases or pests.

Basket willow (cuttings) is most often planted in spring, at the start of the vegetation period, when soil moisture is still high after the winter. It can also be planted in autumn, depending on the local weather conditions.

Cuttings can be hand- or machine-planted. Under the conditions of Poland, in mother plantations or small-area production plantations approximately 32 thousand cuttings are planted per 1 hectare, at spacing of 0.75 x 0.41 m. On larger plantations (over 5 ha) it is recommended to plant cuttings in belts, in double rows. The inter-row spacing in a belt is 0.75 m, and between the belts – 1.5 m. In the rows willow cuttings are most often planted at spacing of 0.44–0.49 m, which results in 18–20 thousand plants per hectare. Such a plantation should be harvested in 3- or 4-year cycles. Directly before planting the cuttings should soaked in water for 24–48 hours.

Harvest is started after natural cessation of vegetation of the plants (October–November) or after the first ground frosts. Harvest can be continued until March.

The acquisition of biomass usually starts after two years of cultivation, in one-, two-, three- or four-year cycles. At the time of harvest the content of water in the shoots is, on average, approximately 50%.

In intensive cultivation, in the first year it is recommended to apply NPK fertilisation at the rate of 40:20:30 $kg \cdot ha^{-1}$, after prior analysis of the soil, while in the second the plants should be fertilised with NPK at the rate of 90:30:90 kg·ha^{-1}. In subsequent years of plantation NPK fertilisation should be applied at 80:30:80 kg·ha^{-1}, keeping in mind that the actual doses of mineral fertilisation should be determined taking into account the soil fertility.

Willow plantations in monoculture can be exposed to infestation by pathogens, pests or weeds, but until now there are no registered preparations for their control. However, so far the levels of pathogen infestation observed are low. Very important in maintaining good health status of plantations of fast-growing basket willow are prophylactic treatments limiting the possibility of occurrence of diseases and pest infestation. These consist in eliminating old willow, aspen or poplar growths and non-productive rootstocks from areas adjacent to the plantation.

The life of basket willow plantations is estimated at 20–25 years. The yields that can be achieved vary from 7 to 20 tons d.m.·ha^{-1} per year, and the calorific value from 15 to 19.5 MJ·kg d.m.$^{-1}$

In spite of the unquestionable advantages of willow cultivation for energy generation purposes, among which one should mention primarily the possibility of establishing plantations on degraded and devastated soils, utilisation of sewage sludge as fertiliser, easy reproduction, its cultivation has also certain drawbacks. There is the risk of drying of cuttings, especially in the case of spring establishment of plantations and on poor soils with a low sorptive capacity. There are also certain critical opinions concerning a negative effect of willow plantations on melioration systems, as the strong and deep-reaching root systems of willow damage drainage systems.

4.2. Giant miscanthus grass (*Miscanthus sinesis gigantheus*)

Miscanthus originates from warm-climate areas of Asia where it has been used for years e.g. for the production of fodders or for covering roofs. In the nineteen thirties it was brought to Europe as an ornamental plant. The giant miscanthus grass (triploid) is a hybrid bred in the eighties of the 20th century in Denmark, from the diploid Chinese miscanthus (*M. sinensis*) and the tetraploid sugar miscanthus (*M. sacchariflorus*).

Under the climatic conditions of Central Europe the plant produces shoots with height of 2–3.5 m and thickness of 1–3 cm filled with a spongy core. Sometimes it produces inflorescences, but no seeds. The leaf blades are dark green, lanceolate in form, with length of 60–100 cm and width of 0.8–3.2 cm. It is a perennial tussock grass producing a strong root system reaching down to 2.5 m. Its reproduction is solely vegetative.

Giant miscanthus grass is characterised by fast growth, high yield of biomass from unit of area, and resistance to low temperatures.

The grass does not have any high requirements as concerns the soil type (classes V, VI), pH should be 6.5. In the first two years the seedlings are very sensitive to low levels of groundwater table (not less than 2 m). The annual sum of precipitations should be about 600–700 mm while the mean annual temperature 8°C (the optimum is 28–32°C).

The most critical period in the cultivation of miscanthus is the first winter, when it displays a high sensitivity to temperatures below zero. To reduce frost damage, plantations are covered with straw. After spring ground frosts the young seedlings regenerate quickly. In the second year after planting the plants are tolerant of temperatures even down -20°C. The grass, with photosynthesis mechanism type C_4, is characterised by a high increase of yields with increasing temperature and solar radiation intensity.

Due to the specific character of multi-year plantations of miscanthus, the soil needs to be prepared carefully before the planting. A winter ploughing is required, preceded with a large dose of organic fertilisers, and intensive weed control treatments are necessary. Plantations of miscanthus are established vegetatively, as the grass does not produce seeds, which may be a desirable feature in the case of seeds of foreign species, as it provides protection against its uncontrolled proliferation.

In view of the sensitivity of the plantings to freezing temperatures, miscanthus is planted at the turn of May and June. The optimum planting density is one plant per 1 m^2, which gives 10 thousand plants per ha. There is no harvest in the first year.

Miscanthus makes efficient use of nutrients and water, as thanks to a well developed root system it can penetrate the soil down to depths of 2.5–3.0 m.

In intensive cultivation, in early spring, after the start of vegetation, it is recommended to apply nitrogen in amounts of 60–90 kg $N \cdot ha^{-1}$. In early spring or in autumn it is recommended to apply fertilisation with phosphorus (30–40 kg $P_2O_5 \cdot ha^{-1}$), potassium (120–150 kg $K_2O \cdot ha^{-1}$) and magnesium (20–25 kg $MgO \cdot ha^{-1}$). At the turn of autumn and winter liquid manure can be applied in the amount of $30 m^3 \cdot ha^{-1}$, which can be a substitute for the mineral fertilisation.

Under European conditions giant miscanthus grass displays a high resistance to most plant pathogens. Prior to establishing the plantation and in the first year of cultivation correct weed control is necessary.

The optimum harvest time is in February or March, which is determined by the water content drop in the plants during the winter period, facilitating mechanised harvest. To avoid damage to the underground rhizomes during mechanised harvest, the operation should be made on frozen soil.

The use of a plantation lasts for about 20 years. Dry matter yield per 1 ha stabilises after 2–3 years from the establishment and varies from 10 to 30 t $d.m. \cdot ha^{-1}$. The calorific value varies from 14 to 17 $MJ \cdot kg^{-1}$, and moisture content, depending on the time of harvest and on the weather conditions, is from 15 to 30%.

An unquestionable advantage of miscanthus cultivation is the possibility of establishing plantations on areas contaminated with industrial pollutants, as the plant uptakes heavy metalsd from the soil rather intensively. It can also be used as an anti-erosion plant.

4.3. Virginia mallow (*Sida hermaphrodita* Rusby)

Virginia mallow, also known simply as mallow, is a perennial plant. It produces tufts of round hollow stalks with diameter of 5–30 mm and height up to 4 m. In the first after the establishment of plantation, the plant produces a single stalk and the number increases to 20–30 in the fourth and subsequent years. The usable yield harvested annually are lignified and dry stalks. Plantations of mallow can be used for periods of 15–20 years.

Virginia mallow comes from North America where it appears in natural conditions. Species from the genus *Sida* desert and semi-desert areas of Africa, Australia, and the Cape Verde islands.

Due to its origin, the plant has no special climate-soil requirements. It grows well on all soil types, even on sandy soils of quality class V, under the condition of sufficient soil moisture. It prefers soils with neutral reaction, possibly slightly acidic. It is resistant to chemical contaminants (heavy metals), and therefore it can be grown in the protective zones of industrial plants, on sewage sludge dumping grounds, municipal waste dumps, and on other industrial grounds.

Mallow is resistant to unfavourable climatic conditions. The plant does not freeze out during hard winters, nor does it dry during hot and dry summers. An increased sensitivity to low temperatures (in the case of poor development of root systems) can only be observed during the year of establishment of plantations.

Good preparation of the field prior to the establishment of a plantation is of particular importance for Virginia mallow. Mallow plantations can be established by sowing seeds (generatively) or planting seedlings (vegetatively). The density for energy purposes varies from 10 to 30 thousand plants per 1 ha. Seeds are sown directly on the field in April, on warm soil, in amounts of 2–3 $kg \cdot ha^{-1}$, the row spacing being 50–70 cm, and that of plants in a row 30–60 cm. Mallow can be successfully reproduced using sections of roots of fragments of aboveground shoots. Plantations of mallow can be established also by planting seedlings prepared before. The production of seedlings should be started in March, so that after the plants have produced 4–6 leaves they can be planted in the field in May.

On energy plantations nitrogen fertilisation should be applied at 50–150 $kg\ N \cdot ha^{-1}$, phosphorus in amounts of 40–120 $kg\ P_2O_5 \cdot ha^{-1}$ and potassium at the rate of 50–100 $kg\ K_2O \cdot ha^{-1}$, starting from the second year of the plantation.

In the year of plantation establishment correct weed control is highly important. The most serious threat in the cultivation of Virginia mallow is white mould. Potential pets classified in the group of crop pests do not do much damage on mallow plantations.

Harvest is started after the natural cessation of vegetation (October–November), after ground frosts (moisture of 35–45%). The biomass harvested at that time is characterised by higher moisture. Stalks harvested in winter are less moist (16–28%).

The life of Virginia mallow plantations is estimated at from 15 to 20 years, the yields vary from 18 to 20 t d.m.·ha^{-1}, and the calorific value from 11.5 to 14.5 MJ·kg d.m.$^{-1}$

The unquestionable advantages of Virginia mallow include its versatile applications as a green fodder plant, honey-bearing, medicinal, a plant suitable for soil remediation, and an energy crop. Unfortunately, the primary limitation of any fast increase of the area of its cultivation is the low germination power of its seeds. However, in spite of both the high labour requirements involved in plantation establishment and the risk entailed, the biomass acquired is very good raw material for the production of low-moisture pellet.

4.4. Jerusalem artichoke (*Helianhus tuberosus* L.)

Jerusalem artichoke, known also as sunroot, sunchoke or topinambour, belongs to the family Asteraceae. It originally comes from North America, but now it is grown on all continents. The height of the plants varies from 2 to 4 m, the raised stems have diameters of up to 3 cm. The leaves are large, with length over 20 cm, oval-cordate, set on long petioles, covered with coarse hairs. The inflorescences are anthodia with diameters up to 8 cm, set at the top of the stems. The fruits are achenes. The plant is entomophilous and has a deep and strong root system. It produces underground stolons at the ends of which there are tubers with protruding eyes and irregular shapes, e.g. fusiform, club-shaped, oval. The colour of the tuber skin can be white, yellow or red of various shades up to purple.

Jerusalem artichoke has moderate climatic requirements, is tolerant of variable weather conditions and low temperatures. However, the most favourable for the species is warm and humid weather. It grows best on medium compacted soils, well aerated, with high levels of nutrients and sufficient moisture. Whereas, it yields poorly on waterlogged and acidic soils.

In the cultivation of Jerusalem artichoke careful soil cultivation and proper choice of stand are very important. The forecrops for the species can be all crop plants and not overly weedy fallows. The arable horizon must be deep (25–30 cm). Jerusalem artichoke is planted in autumn (November–December) or in early spring (March–April). Planting density is 3–4 tubers·m^{-2}, which is equivalent to 1.5–2.5 tons of sets per hectare. The distances between rows should be 0.7–1.0 m, and plant spacing in a row 0.5–0.6 m.

Jerusalem artichoke is reproduced only vegetatively. The tubers produce roots and germinate at soil temperature of 4–5°C. Autumn planting appears to be more beneficial, as the plants start vegetation before the soil dries and is suitable for mechanical tillage. As a result, the vegetation period of Jerusalem artichoke is longer by at least 3 weeks, which is favourable for yielding.

Jerusalem artichoke is most often cultivated outside of crop rotations, for several or more years on the same field, and therefore so-called renovation of plantation is required. Compared to the other energy crops, the maintenance of plantation in good condition requires a lot of labour, and leaving it without thinning out causes that it becomes non-effective. Excessive density of canopy of Jerusalem artichoke results in a reduction of yields – both of green matter and tubers.

With average levels culture and soil fertility the recommended fertilisation doses are as follows: nitrogen 80–120 kg N·ha^{-1}, phosphorus 60–80 kg P_2O_5·ha^{-1} and potassium 120–160 kg K_2O·ha^{-1}.

Required treatments include harrowing of the plantation after emergence, weeding of the inter-rows, earthing up. Jerusalem artichoke is resistant to diseases and pests.

The timing and frequency of harvest are dependent on the purpose of cultivation (for tubers or for green matter). Tuber harvest is done mainly in late autumn, before the frosts. When planning a spring time of tuber harvest, stems are cut in winter during frost to avoid compacting the soil with the wintering tubers. However, that is not a good time, as then the stems are felled by the wind, snow, rain, which causes problems with the harvest and lower yields. The harvest of the aboveground parts can be made as early as October (after drying of the stems).

The yields of fresh biomass (combined: tubers – moisture of 74–86% and aboveground parts – moisture of 45–50%) vary from 150 to 180 t·ha^{-1}, i.e. 20–25 t d.m.·ha^{-1}, and the calorific value is 15–16 MJ·N d.m.$^{-1}$

Jerusalem artichoke is characterised by a very high production potential, possibility of self-renovation and versatility of applications: for energy generation, as fodder for cattle, sheep, pigs (both tubers and underground parts), herbal medicine. Its shortcomings include high volume of biomass after harvest, as well as poor yields on waterlogged and acidic soils.

The above characterisation was elaborated on the basis of the following literature sources:

1. Album of Energy Crops. Virginia mallow (in Polish). Polska Izba Biomasy. June 2006.
2. Borkowska H., Molas R., 2012. Two extremely different crops, *Salix* and *Sida*, as sources of renewable energy. Biomass and Bioenergy. Vol. 36, 234–240.
3. Gniazdowski J., 2009. Estimation of biogas yield for a planned biogas facility at a milk cow farm (in Polish) Inż. Rol. 3, 67–73.
4. Kabała C., Karczewska A., Kozak M., 2010. Suitability of energy crops for the reclamation and utilisation of degraded soils (in Polish). Zeszyty Naukowe Uniwersytetu Przyrodniczego we Wrocławiu. Rolnictwo XCVI. Nr 576, 97–117.
5. Kowalik P., 2002. Willow energy crops (in Polish). Czysta energia 6, 8–9.

6. Michałowski M., Gołaś J., 2001. Content of selected heavy metals in willow organs as an indicator of its use in the utilisation of sewage sludge (in Polish). Zesz. Probl. Post. Nauk Rol., 477, 411–419.
7. Prośba-Białczyk U., 2007. Productivity of Jerusalem artichoke (*Helianthus tuberosus* L.) cultivated without fertilisation (in Polish). Fragmenta Agronomica. Vol. XXIV. Nr 4 (96), 106–111.
8. Szczukowski S., Tworkowski J., Wiwat M., Przyborowski J., 2002. Willow (*Salix* sp.). Cultivation and possibilities of utilisation (in Polish). Wydawnictwo UWM Olsztyn, 7–25.
9. Szczukowski S., Tworkowski J., Stolarski M., Kwiatkowski J., Krzyżaniak M., Lajszner W., Graban Ł., 2012. Perennial energy crops (in Polish). Monograph. MULTICO Oficyna Wydawnicza. Warszawa, 156.

5. Methods of research

The objective of the study was the estimation of the possibility of modelling of the effect of weather conditions on the variation of actual evapotranspiration and on the yields of green matter of four energy crops (giant miscanthus grass, Virginia mallow, basket willow and Jerusalem artichoke) during the vegetation period, under conditions of varied availability of water. That objective was to be achieved on the basis of a field experiment and logical and statistical analysis of the results obtained from the field measurements.

For the achievement of the above objective the following questions were posed:

1. Is there a possibility of a simple mathematical notation of the relation of evapotranspiration of energy crops during the vegetation period to the course of the meteorological conditions?
2. Is it possible to estimate the reduction of yields of energy crops resulting from unfavourable weather conditions?
3. Is it possible to develop regional distribution recommendations for energy crops in relation to climate conditions and potential availability of water?
4. To what extent can the thermovision technique be applied for imaging the spatial variation of the intensity of evapotranspiration of energy crops in relation to their access to water.

Planning the realization of the adopted objective it was assumed that the results concerning evapotranspiration under conditions of varied water availability for plants, collected in the course of the field experiment, in combination with the selected group of agrometeorological factors, would permit the estimation of the environmental determinants. It was also assumed that they would permit the determination of periods for which the best correlations can be obtained between the yields of the energy crops, the water resources of the soil and the particular agrometeorological factors. On that basis we could get the answer in what way the weather and climatic conditions affect the growth and yielding of selected energy crops, and estimate the periods inhibiting or stimulating plant growth. The statistical analysis was to consist in the development of statistical relations between the selected group of agrometeorological factors and the values of evapotranspiration of the particular energy crops for various time intervals. The indices of significance of the equations developed would be the coefficient of determination of the developed regression equations. Their analysis was to permit the identification of those meteorological elements that are significantly correlated with the evapotranspiration of the particular energy crops in various growth phases for various time intervals. The aim of that procedure was the determination of periods for which the best correlations can be obtained between the yields of the energy crops, water resources of the soil, and the particular agrometeorological factors. That approach can, in turn, create a foundation for estimations concerning the choice of regions for the cultivation of energy crops under conditions of diversified climate and access to water. It would also permit, based on the results obtained from field observations, to build mathematical models with various scales of complexity for the estimation of evapotranspiration and of the growth of green matter of energy crops during the vegetation period. Due to the short, only three years, period of realization of the project it was decided to acquire information on the dynamics of growth of green mater of the particular energy crops, as the limitation to information on only the final yields would be difficult to interpret due to the fact that there is possibility to predict the weather conditions over a longer time horizon. Only recording the changes of the individual agrometeorological factors during the vegetation period permits referencing the results obtained to values from a multi-year period and thus to acquire information on the level of changes of the selected factors that comprehensively build the status of the weather in the consecutive years. The situation is analogous in the case of predicting the yields of energy crops.

In the world literature there are no published reports on studies concerning the evapotranspiration of energy crops conducted over long time intervals from the establishment of a plantation to its physical liquidation. Studies conducted in that way should provide an answer to the question for what optimum time a plantation should function under specific soil and meteorological conditions. For this reason the authors of this project undertook a study aimed at investigating the process of evapotranspiration with 1-day time step for selected energy crops under conditions of varied availability of water. The results of the study are valuable, as the research was started in the second and ended in the fourth year of the existence of the plantation. The plantation has not been liquidated, and the study will be continued. The three years of detailed measurements and analyses coincided with a period of dynamic, in the opinion of the authors, increases of green matter of the energy crops.

6. Characterisation of the research object

6.1. Situation of the Agro- and Hydrometeorological Observatory Wrocław-Swojec

Fig. 1. Schematic map of the research area and its surroundings.
The location of the Agro- and Hydrometeorological Observatory is indicated with an arrow

To realize the assumed objective of the field experiment, the studies were conducted at the Agro- and Hydrometeorological Observatory of the University of Environmental and Life Sciences in Wrocław, within the area of the Agricultural Experimental Station Wrocław-Swojec. The Station is surrounded with fields and meadows. The straight line distance from the bank of the River Odra is 2200 m. The object is separated from the city centre of Wrocław with a complex of parks and stadiums, and with the river Odra channel, meadows and fields (Fig. 1). The Observatory in Swojec is situated at an altitude of 120.7 m a.s.l., geographic latitude 51°07', longitude 17°07'. The situation of the experiment within the area of the Agro- and Hydrometeorological Observatory in Wrocław-Swojec permitted comprehensive monitoring of plants on the experimental plots and in the evaporimeters, and of the weather conditions in the course of the experiment. The comprehensive evaluation of changes of the weather conditions in the course of the field experiment was made with the use of standard meteorological data collected continuously in the area of the Agro- and Hydrometeorological Observatory Wrocław-Swojec of the University of Environmental and Life Sciences (Phot. 1).

6.2. The description of the field experiment

The observations conducted routinely at the Observatory include, among other things, the following; atmospheric precipitation – measured at two times by means of the standard Hellmann pluviometer, solar radiation and insolation, air temperature – measured in a Stevenson screen at a height of 2 m, wind velocity, at a height of 10 m, groundwater level – in piezometers situated near the experimental plots with energy crops (Phot. 2). For the estimation of the evaporation capacity of air, continuous measurements of evaporation from a free water surface are conducted with the use of a programmable evaporimeter EWP 992 with automatic data recording at any chosen time step (Phot. 3).

The field experiment consisted in measurements of actual evapotranspiration of four energy crops (giant miscanthus grass, Virginia mallow, basket willow and Jerusalem artichoke) in 32 soil evaporimeters with surface area of 0.3 m^2 situated in the area of the Observatory (Phot. 4). The measurements were taken twice a day, like the measurements of precipitation.

Seedlings of basket willow and Virginia mallow were planted at spacing of 70 by 40 cm, those of giant miscanthus at 70 by 100 cm, and Jerusalem artichoke – 70 by 30 cm. A schematic of the layout of the experiment, including the situation of the plots with the energy crops and their planting spacing, is shown in Figure 2.

To avoid the oasis effect, the plantings on the energy crop plots around the evaporimeters were done in such a way that the plants in the evaporimeters were distributed in rows in conformance with the distribution of the plants on the plots. The method and the effect of the planting is presented on the example of Jerusalem artichoke and willow (Phot. 5).

The plan of the experiment assumed the use of one-year old plants (20 evaporimeters, 5 per plant species) and two-year old plants (12 evaporimeters, 3 per plant species), and on the plots neighbouring the soil evaporimeters. The evaporimeters were placed within the plant canopies to avoid the oasis effect. The field experiment included two variants of water supply for all the energy crops. The first variant concerned the plants growing in the soil evaporimeters. The use of those devices permits a situation where plants growing in evaporimeter pots can only use water from precipitations due to the lack of contact of the soil monoliths with ground water.

Phot. 1. General view of the Agro- and Hydrometeorological Observatory Wrocław-Swojec

Phot. 2. Groundwater level measurement station on the plots with energy crops at the Agro- and Hydrometeorological Observatory Wrocław-Swojec

Phot. 3. Evaporimeter EWP 992 on a measurement site at the Agro- and Hydrometeorological Observatory Wrocław-Swojec

Phot. 4. View of the experimental plots with energy crops in the area of the Agro- and Hydrometeorological Observatory Wrocław-Swojec

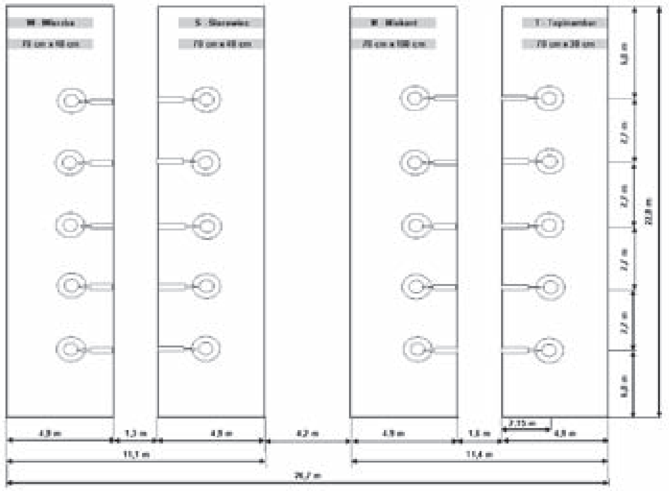


Fig. 2. Layout of the experiment with energy crops on the plots and in the evaporimeters within the area of the Observatory Wrocław-Swojec

Phot. 5. Method of energy plants distribution on the plots

The principle of operation of soil evaporimeter consists in periodic measurements of changes in soil mass in the pot, caused by evaporation and filtration to its deeper layers. In the case of irrigations or precipitations very accurate estimation of the values of such changes is necessary. To determine the evapotranspiration of crop plants, the surface area of evaporimeters should ensure soil mass in the pot corresponding to the requirements of the root layer. For this reason the evaporimeters used in the field experiment had soil monoliths with depth of 0.7 m placed in steel pots with a larger diameter, permitting the isolation of the evaporimeters from influx of ground waters.

The original design of soil evaporimeters, with surface area of 3000 cm^2 and depth of 80 cm, was based on evaporimeter GGI–3000, used in the hydrological network of the former USSR, which had surface area of 3000 cm^2 and depth of 100 cm. The divergence from the original was caused at that time by the availability of cranes and balances for handling weights not greater than 500 kg. The bottom of the pot has 100 apertures with diameter of 4 mm. This is to ensure the possibility of free outflow of excess water from the soil monolith, above the field water capacity of the soil. After placing a soil monolith in the evaporimeter cylinder, the perforated bottom is attached to the bottom part of the pot by means of clamps. The design of the device permits multiple measurements of changes in the weight of the individual pots within a day over the entire period of vegetation of the particular plants, with simultaneous monitoring of the downward outflow that occurs after the field water capacity of the soil is exceeded. The water from that outflow is collected beneath the soil monolith and does not get in contact with the ground water outside of the pots. Due to the limited volume of the space beneath the evaporimeter and to prevent the possibility of flooding by the water filtering out from the soil monoliths and collected under the pots, the pots are periodically emptied. The frequency of that operation depends primarily on the value and frequency of atmospheric precipitations.

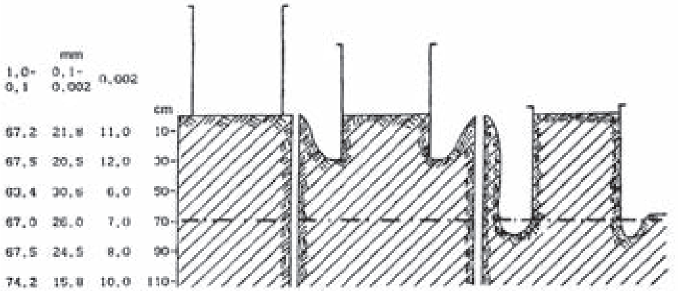


Fig. 3. Schematic of the method of taking a soil monolith with undisturbed structure into a cylinder – pot

Filling the pots can be done in early spring or in autumn, depending on the technical possibilities and low groundwater levels in the area where soil monoliths are taken. Pots are filled with soil monoliths in the field, together with plants planted earlier or without plants in the case of energy crops. After the filling the pots are placed at the measurement sites, where they will be surrounded with cultures of the same plants on the experimental plots to avoid the oasis effect. The taking of soil monoliths with undisturbed structure is presented in Figure 3, while the detailed method and procedure of sampling and transport to measurement sites is described in the work [Bac 1970].

The evaporimeter design and operation method described in that reference did not allow correct estimation of field evaporation over periods shorter than a decade. For this reason, as a result of numerous tests a prototype was developed whose chief constructor was Jan Jangas [Utility pattern No. 59735]. The application of that new device permitted measurements with accuracy of 0.1 mm, for each day, also in the inter period. The operation has become considerably simplified as it now consists only in reading the position on the pointer on the scales of mass value and filtrate volume. After patenting the device it is now known under the name "Device for measurement of changes in soil water retention and downward outflow UPZR" [Utility pattern No. 59735] (Fig. 4).

Studies conducted with the help of evaporimeters of the new design permitted measurement of field evaporation for a specific kind of soil and its natural structure, while maintaining the number and density of plants per unit of area in accordance with the agronomical recommendations and the natural environment of the pots. Independence was gained from errors in measurements of atmospheric precipitation, as the changes in pot mass were now caused by influx in the form actual precipitation or irrigation reaching the soil surface, minus the interception and water outflow down the soil profile from the canopy substrate.

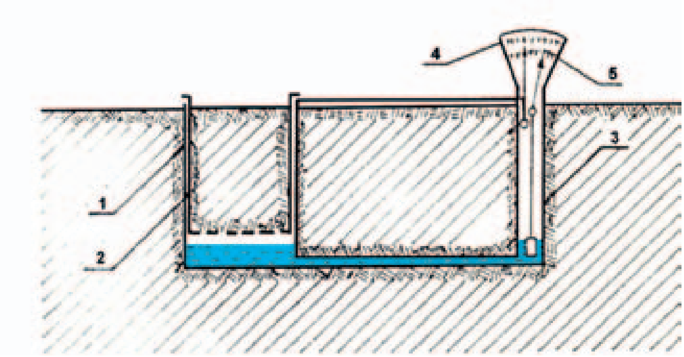


Fig. 4. Soil evaporimeter design in cross-section. 1 – outer casing, 2 – pot, 3 – well for filtrate measurement, 4 – scale of mass changes, 5 – scale of water level changes

During the period of the field experiment with the energy crops the positions of the pointers on the scales of changes of mass and filtrate volume were read every day during the morning and evening observations, over the period from April till mid-November. The results of measurements were recorded in logs of evaporimetric measurements (Fig. 5). This permitted particular care in the studies on evapotranspiration with regard to the similarity to natural conditions of the plants in the evaporimeters which, as a rule, grew surrounded by the same plants at identical canopy density.

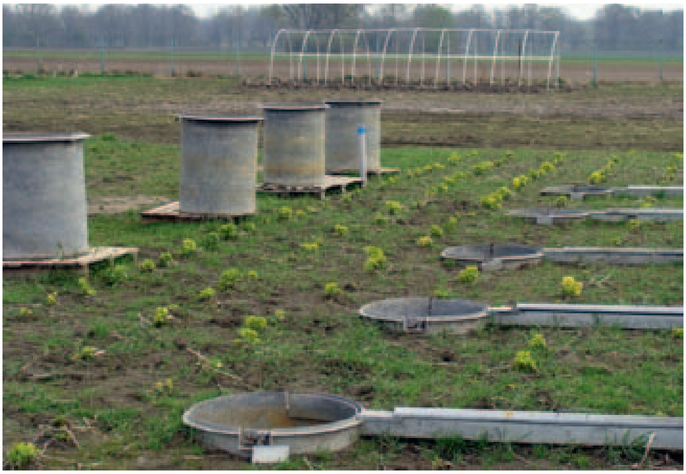
Pomiar parowania terenowego Ewaporometr Wierzba nr 5

Uniwersytet Przyrodniczy we Wrocławiu Miesiąc - sierpień Rok ....

Data	Waga	△ q	Przesiąk	△ s	podpis	Data	Waga	△ q	Przesiąk	△ s	podpis
1						17					
2						18					
3						19					
4						20					
5						21					
6						22					
7						23					
8						24					
9						25					
10						26					
11						27					
12						28					

Fig. 5. Fragment of the log of measurements of field evaporation of energy crops conducted at the Agro- and Hydrometeorological Observatory Wrocław-Swojec

The pots with soil monoliths for the energy crops, prepared for installation, are presented on Photo 6. Prior to installation every evaporimeter pot was weighed (Phot. 7).



Phot. 6. Evaporimeter pots prepared for installation at the measurement sites in the Agro- and Hydrometeorological Observatory Wrocław-Swojec

Phot. 7. Measurement of evaporimeter mass prior to its installation at a measurement site in the Agro- and Hydrometeorological Observatory Wrocław-Swojec

After measuring the mass of the evaporimeters, each of them was installed at a separate measurement site in the designated experimental plots of the energy crops (Phot. 8). To ensure correct measurements of changes in the mass of the evaporimeters resulting from changes in the values of evaporation and water filtration through the soil monoliths it is necessary to position them carefully on the prisms installed in their outer casings.

Phot. 8. Installation of evaporimeter at a measurement site in the Agro- and Hydrometeorological Observatory Wrocław-Swojec

A considerable difficulty in that operation is the limited possibility of precise manoeuvring the evaporimeters pots due to their large weight of close to 500 kg.

Within the scope of the project soil temperature was monitored continuously at depths of 10, 20, 40 and 60 cm in the soil profiles in the evaporimeters and on the particular experimental plots, and soil moisture was measured with the use of the TDR technique. For this reason, another organisation task was the installation of instruments for soil moisture and temperature monitoring in the evaporimeters and in the area of the plots with the energy crops. The TDR method, i.e. the measurement of soil moisture with the use of Time Domain Reflectometry, is one of the most modern methods of soil moisture measurement, replacing the commonly applied thermo-gravimetric method which is highly labour-consuming and has limited applicability. The measuring device is a multiplexed sensor of soil moisture, salinity and temperature type DR/MUX/mts with data acquisition system MIDL_GPRS for field installation (various depths of installation). The system permits continuous measurement at the same point, with programmable time step. The method is based on measurement of the velocity of propagation of an electromagnetic wave with frequency above 50 Mhz, induced by TDR, that is dependent on the dielectric constant (K_a) of the medium in which the measurements are conducted. As an example, for water its value is 81, for the solid phase of soil 3÷8, and for air 1. Due to the fact that water has the highest value of K_a, it has the decisive effect on the value of the dielectric constant of the soil studied. The principle of reflectometric measurement of the velocity of electromagnetic impulse in soil is presented in Figure 6.

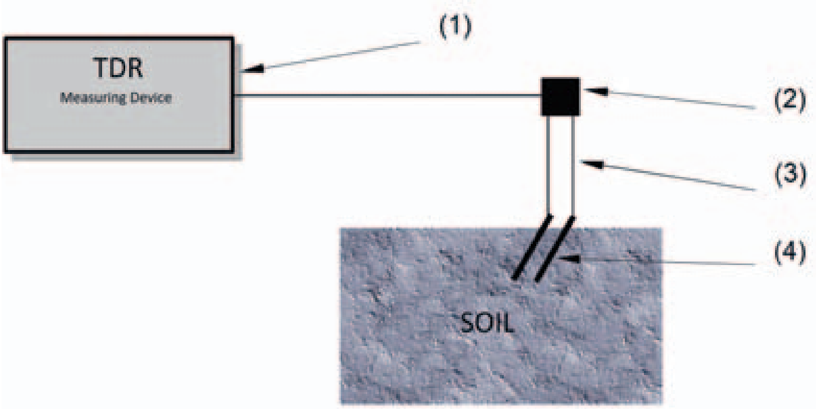


Fig. 6. The principle of reflectometric measurement of velocity of electromagnetic impulse in soil

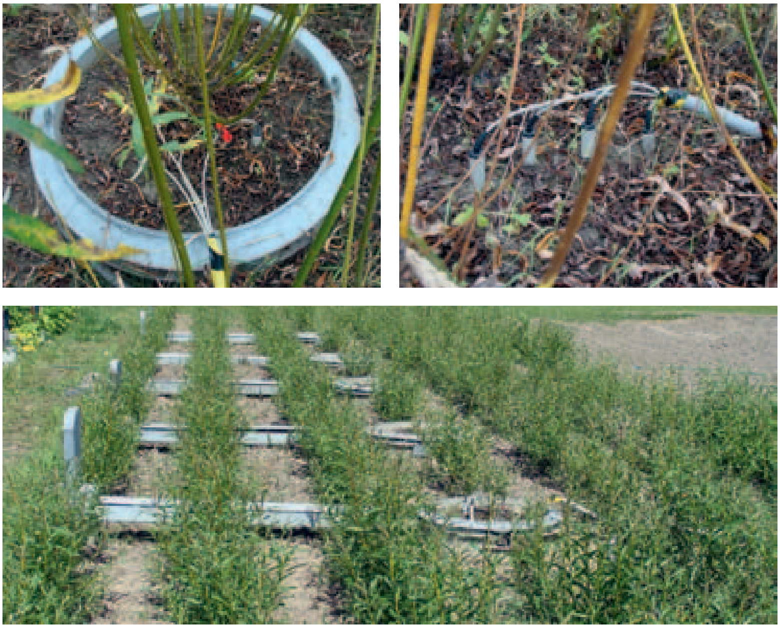
The probes are made of two parallel non-insulated rods which are inserted in the soil. The transmitting probe is connected with the TDR measurement unit TDR (1) by means of a concentric cable. The generator, located in the measurement unit, generates and sends electromagnetic wave pulses that, passing through the holder cylinder (2), undergoes an increase of voltage due to the difference between the dielectric constant values of the cable and the holder cylinder. Then the wave travels along the balanced pair of conduits (3) until it enters the soil where a large part of the signal is reflected back to the generator, which is observed as a drop of voltage. The remaining part of the wave travels into the depth of the studied soil, along the electrodes (4). When the wave reaches the tips of the electrodes its principal reflection takes place, and return to the generator (3, 4). The value of the attenuation of the reflected wave depends on water content in the soil, and also on the concentration of electrolytes and on the content of clay particles. The detailed principles of installation and methods of measurement are given in a manual [Easy Test D – LOG- Manual] prepared by the Institute of Agrophysics PAS in Lublin.

The functionality of the method is confirmed in numerous studies [Baruah and Hasegawa 2001, Lundberg 1997, Malicki and Kotliński 1998, Mastrorilli et al. 1998, Skierucha and Walczak 2005]. It can be applied not only for the determination of soil moisture, salinity and temperature, but also for the moisture of cereals and wood, or other materials with porous texture. Taking into account the values of the method and the equipment limitations of the experiment, it was decided to install TDR probes in selected evaporimeter pots. The method of their installation is presented in Photos 9, 10, 11 and 12.

Phot. 9. TDR probes installed in a plot and an evaporimeter under Jerusalem artichoke

Phot. 10. TDR probes installed in a plot and an evaporimeter under *Miscanthus sinesis gigantheus*

Phot. 11. TDR probes installed in a plot and an evaporimeter under Virginia mallow

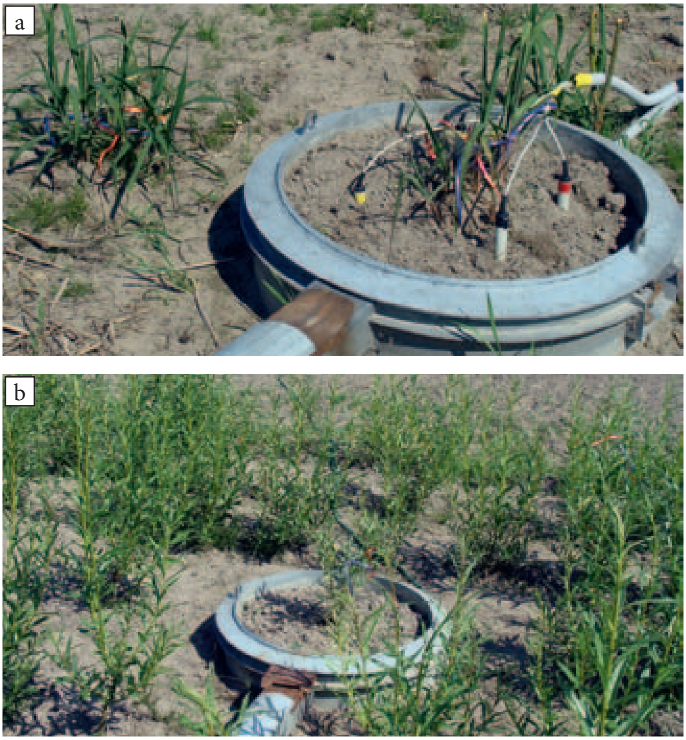


Phot. 12. TDR probes installed in a plot and an evaporimeter under basket willow

For the purpose of determination of the value of evapotranspiration of the particular energy crops, comparative measurements were conducted with 6 evaporimeters that had soil monoliths with bare soil and with soil covered with lawn (Phot. 13).

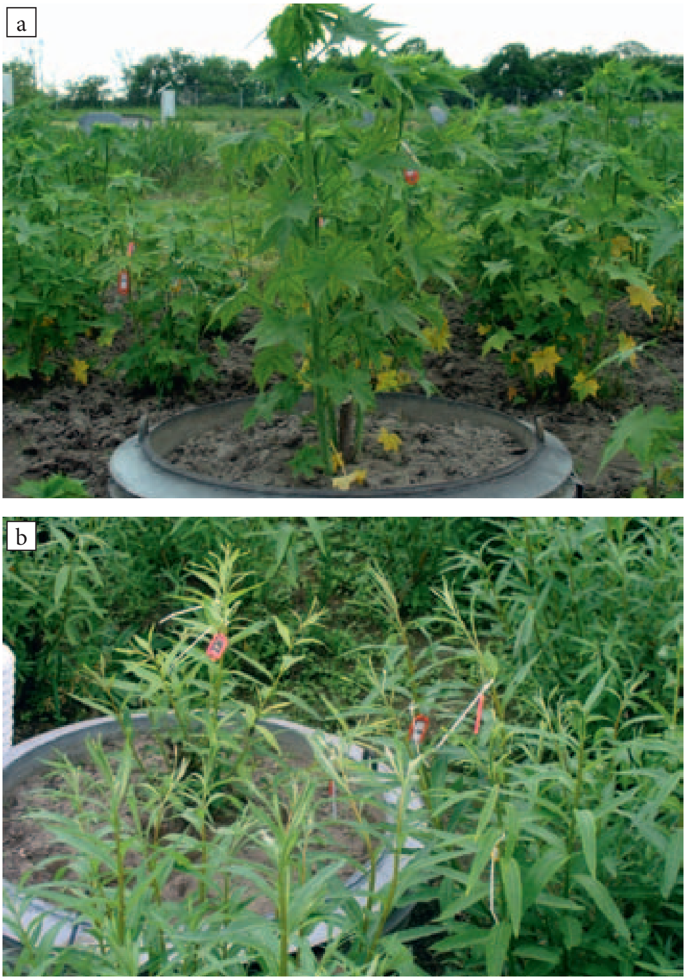
Phot. 13. Evaporimeters UPZR with bare soil and with soil covered with lawn at the Agro- and Hydrometeorological Observatory Wrocław-Swojec

The second variant assumed the study and biometric observations of plants growing on the plots around the evaporimeters. Those plants, apart from atmospheric precipitations, could freely make use of water through capillary rise from the groundwater level, and thus had natural conditions compared to the plants growing in the evaporimeters, where the amount of available water was limited to the influx from atmospheric precipitations and sedimentation. Due to the need of estimating the dynamics of mass increments of the particular energy crops it was asumed that, in parallel to the evaporimetric measurements, biometric measurements would be conducted for plants in the evaporimeters and on the surrounding experimental plots. The estimation of mass increments of growing plants requires knowledge of such parameters as the length of the produced shoots or stems, their number, and their diameter. That permitted – with the comparison of evaporation measurements of the bare soil surface in the evaporimeters and that with growing energy crops – to estimate the correlations between the values of evaporation itself and of the evapotranspiration of the energy plants during the vegetation of the plant mass. Such measurements should be conducted on the same plants, and for that reason plants were chosen in the evaporimeter pots and on the plts outside of the pots, and the shoots which were subjected to the biometric measurements were suitably marked (Phot. 14).



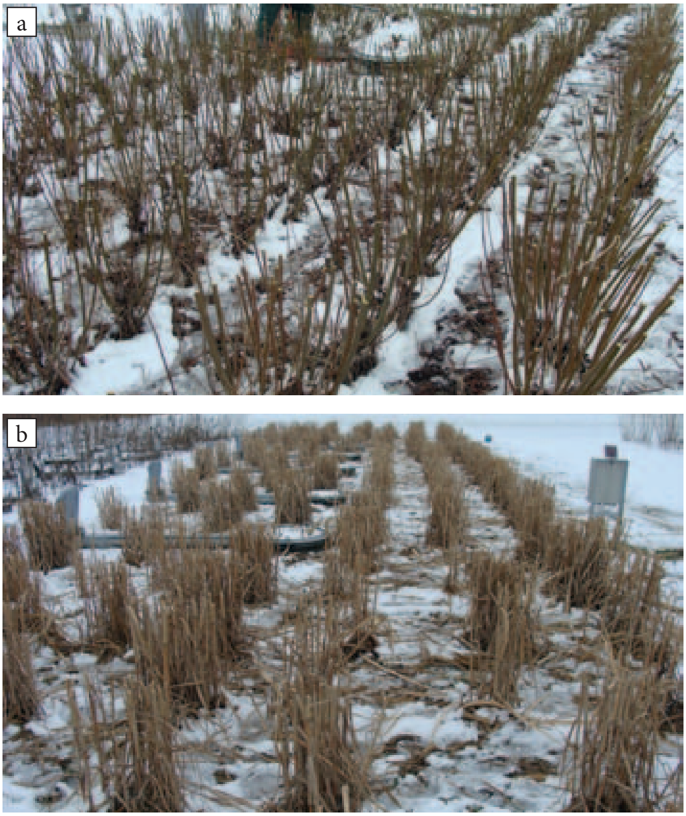
Phot. 14. Markings placed on energy plants covered by the biometric measurements in the evaporimeter pots and growing nearby. Examples (a – miscanthus and b – willow)

Initially, for the identification of plants selected for the measurements they were marked with colour ribbons that, with the passage of time during the vegetation period, became poorly visible (Phot. 14). The poor visibility resulted from the dynamic growth of the plants, obscuring the initial markings. That created a considerable problem with finding the marked plants and shoots, while the low durability of the markings resulted from rapid fading of the ribbons used for the markings due to exposure to sunlight, which would make it hard to identify the particular plants and shoots for subsequent biometric measurements. Finally it was decided to use popular key-ring tags. This way of marking permitted more visible colour differentiation as well as allowed permanent text markings on the plants, lasting for the entire period of vegetation (Phot. 15).



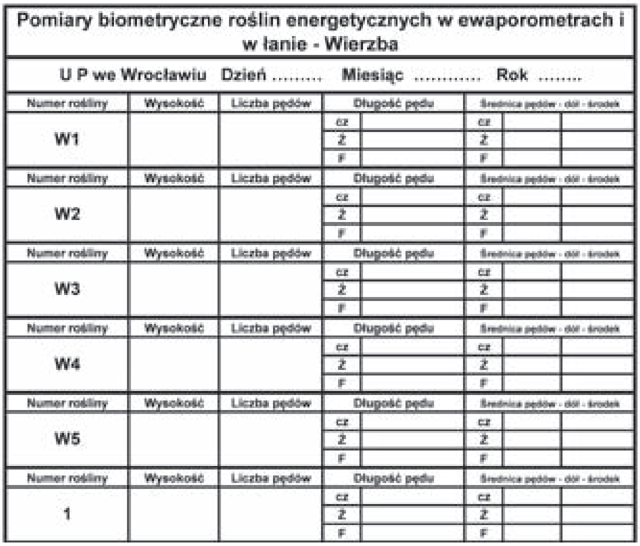
Phot. 15. Markings placed on energy plants covered by the biometric measurements in the evaporimeter pots and growing nearby – after modification
Examples (a – mallow and b – willow)

Every time the measurements were made on the same 5 bushes of each energy plant, at weekly intervals. The biometric measurements were started when the plants on the plot attained the height of 0.5 m. Each time the number of shoots per bush was also counted, and the length and diameter at the mid-point of 3 selected and marked shoots (every time the same ones) were measured, as described above. In the literature no rules were found as to the height of shoot at which its diameter should be measured when making the biometric measurements. The heights of measurement adopted are varied [e.g. Amichew et al. 2011]. At the same time, several-year observation by the authors of this experiment indicate a large variation in shoot diameter from the base to the height of ca. 35 cm, and a notable tendency to drying in the case of shoots with lengths below 0.5 m. For this reason it is justified to begin biometric measurements on those plants and shoots which attained the height of minimum 0.5 m. At the end of every vegetation period all shoots with length above 0.5 m were counted, for each plant growing on the plantation. To make that task easier, after the stop of vegetation the plants were trimmed before the count was taken (Phot. 16).



Phot. 16. Energy plants prepared for the shoot count on the whole plantation – in the evaporimeter pots and growing nearby. Examples (a – willow and b – miscanthus)

The planned measurement of evapotranspiration would not be correct without taking into account the mass of the growing plants. For this purpose it was planned to apply corrections of evapotranspiration related with the increase of the plant mass. The corrections were to consists in a procedure whereby every 2 weeks plant material was to be collected from the plots surrounding the evaporimeters, with morphological features similar to those of the plants growing in the evaporimeters. For the same reason that assumption was changed in the course of the field experiment, finding that the two-week intervals were too long. That observation was made in the first year of the functioning of the experimental plots. It was noted that the two-week period was too long as already during one-week periods there appear considerable increases in the aboveground parts of the plants. Therefore, henceforth the biometric measurements were made at one-week intervals. The results of those measurements were recorded on special measurement logs (Fig. 7).



Pomiary biometryczne roślin energetycznych w ewaporometrach i w łanie - Wierzba

U P we Wrocławiu Dzień .... Miesiąc .... Rok ....

Numer rośliny	Wysokość	Liczba pędów	Długość pędu		Średnica pędów - dół - środek		
W1			cz		cz		
			Ż		Ż		
			F		F		
Numer rośliny	Wysokość	Liczba pędów	Długość pędu		Średnica pędów - dół - środek		
W2			cz		cz		
			Ż		Ż		
			F		F		
Numer rośliny	Wysokość	Liczba pędów	Długość pędu		Średnica pędów - dół - środek		
W3			cz		cz		
			Ż		Ż		
			F		F		
Numer rośliny	Wysokość	Liczba pędów	Długość pędu		Średnica pędów - dół - środek		
W4			cz		cz		
			Ż		Ż		
			F		F		
Numer rośliny	Wysokość	Liczba pędów	Długość pędu		Średnica pędów - dół - środek		
W5			cz		cz		
			Ż		Ż		
			F		F		
Numer rośliny	Wysokość	Liczba pędów	Długość pędu		Średnica pędów - dół - środek		
1			cz		cz		
			Ż		Ż		
			F		F		

Fig. 7. Fragment of the log of biometric measurements of the energy plants maintained at the Agro- and Hydrometeorological Observatory Wrocław-Swojec

Another problem that was to be investigated was the possibility of application of the thermovision (IR) technique for the estimation of evapotranspiration in spatial scale and to relate that process with evaporation from free water surface measured by means of evaporimeter EWP 992. The preliminary tests in this scope conducted in the area of the Agro- and Hydrometeorology Observatory in Wrocław suggest that that technique can be useful for indirect estimation of the intensity of the process of evapotranspiration.

7. Characterisation of soils in the research object

First professional hydrogeological-pedological investigation in the area of the Agro- and Hydrometeorological Observatory of the adjacent fields was conducted in the years 1964–1965 [Mazij et al. 1965]. Two kinds of texture were identified in the soils of that area:

1. Sands and loamy sands overlying loam,
2. Deep sands (sandy texture throughout the soil profile).

However, as admitted by the authors of that analysis, those definitions are conventional and can only be used for the description of the soils for e.g. cartographic purposes. The soils on the fields designated for this study (Fig. 8) are primarily sands (Polish class "piasek słabogliniasty") and loamy sands (Polish class "piasek gliniasty lekki").

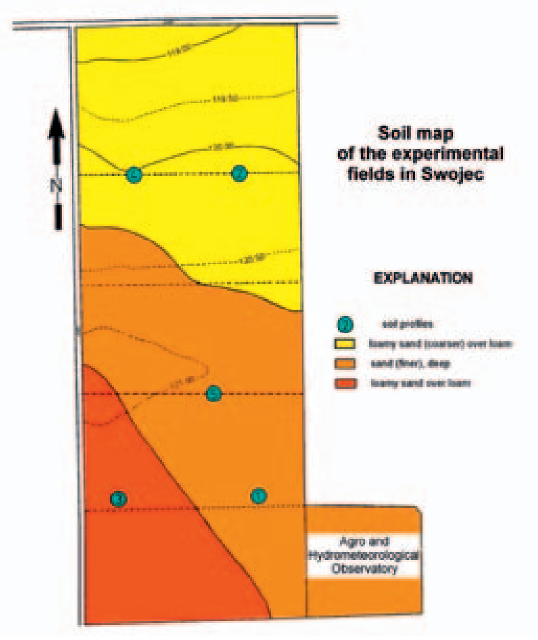


Fig. 8. Schematic map of soils in the area of the Agro- and Hydrometeorological Observatory and the adjacent fields [based on Mazij et al. 1965]

The cited analysis states that the loam starts at depths from 3.3 m to 5.0 m below ground level (BGL) and forms an impermeable layer, underlying the entire experimental field. In addition, there is a second loamy, impermeable layer at depths 1.07–1.8 m BGL in some of the fields. According to contemporary genetic soil classification, the soils were classified as arable brown earths developed from glacial till (boulder loam) with surface sandy layer. The maximum water capacity in the area of the fields varies from 306 to 340 mm in an upper, 100 cm thick soil layer. The mean value for the entire object is 323 mm. Good water properties of the soils are indicated by high field water retention capacity, in average 217 mm in the 100 cm thick upper layer. The mean wilting point is at about 5% water content. However, due to the distant time of that analysis, the analyses of the soils, with particular emphasis on the surroundings of the Agro- and Hydrometeorological Observatory, were updated and expanded in 2012.

7.1. Outline of geological structure

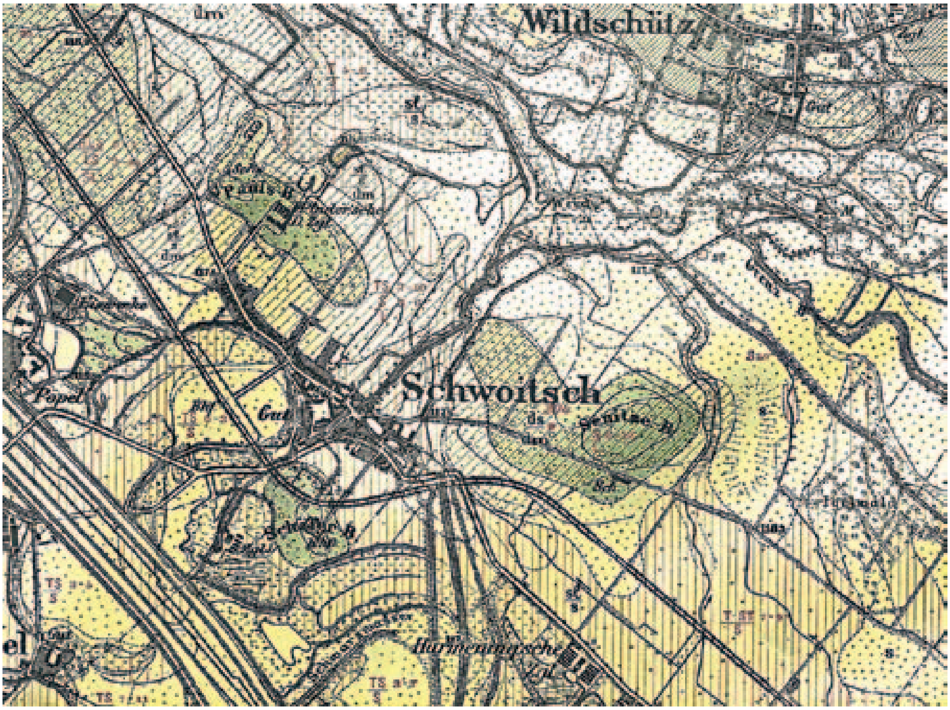
7.1.1. Review of existing geological and hydrogeological materials

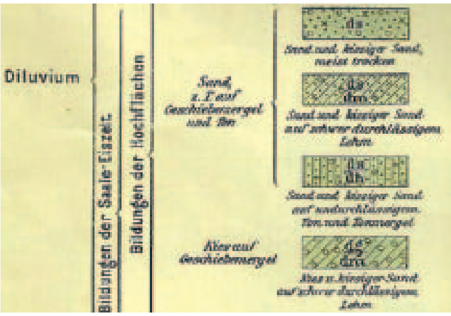
Based on the situation of the Agricultural Experimental Station Swojec in the fork of rivers Odra and Widawa one could conclude that the whole area is covered solely with contemporary alluvial sediments with considerably thickness. However, already the earliest studies revealed a much more complex picture, including a large spatial lithological variation of the sediments.

The first German detailed geological map [Tietze and Behr 1927] reveals that the plain hill in the central part of the present-day experimental station (Senitzeberg) is built of "diluvial" sands, i.e. sands deposited during glacier melting over underlying moraine loams of the Saale glaciation, known in the Polish geology as the Odra glaciation (Fig. 9). Variable thickness of the sand cover exceeds locally 2 metres. The greatest thickness of sands was found not in the central (highest), but in the northern part of Senitzeberg. The glacial loam (till) builds the bedrock of the hill and extends at ground surface in the north-western direction. In the surrounding area, both to the south and to the north, there are also loams covered with sands, but at notably greater depth. At a greater distance from the hill, especially to the east (beyond the channel Senitze-Graben) and north (in the direction of the boundary ditch and river Widawa), there dominate the deep alluvial sands, sometimes loamy or peaty. Senitzeberg is therefore one of the "glacial islands" among the alluvial deposits of the valleys of Odra and Widawa rivers.

Also other such islands were distinguished in the vicinity of the village Schwoitsch, e.g Schaeferberg, Paulsberg, Kretschamberg, Fuchsberg etc. Those islands are interpreted as remnants of a "ridge" (moraine chain) built of glacial loams and sands, originally dividing the valleys of the Odra and the Widawa. In the north-western direction (in Wrocław city) those formations extend considerably and are much better preserved.

The publication of the geological map coincided with detailed investigation of the geological structures of the surface layers in the area of university experimental station at Swojec [Kraut 1927]. On a regular square grid 100 m per 100 m, the 185 soil pits were dug to the depth of 120 cm and deepened by drilling down to 200–220 cm. That work provides





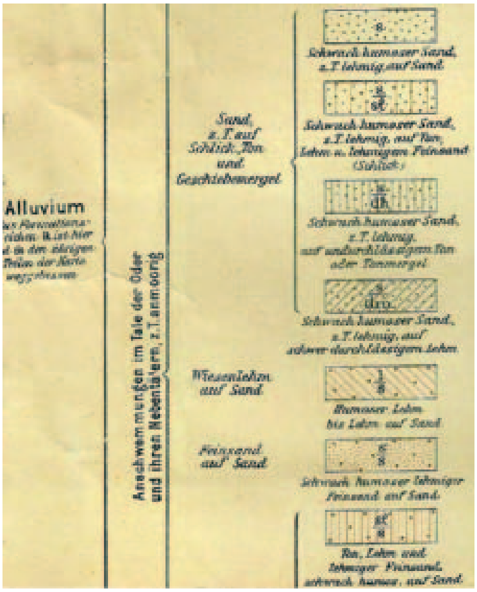


Fig. 9. Geological structure of settlement Schwoitsch according to the first detailed geological map [Tietze and Behr 1927], sheet Breslau (Nord).
Legend: s – weakly humus sand, occasionally loamy, over sand (alluvium), s/dm – weakly humus sand, occasionally loamy (alluvium) over impermeable glacial loam, sl/s – clay, loam or fine-grained loamy sand, weakly humus, over sand (alluvium); ds – sand and gravelly sand (glacio-fluvial – "diluvium"), ds/dm – sand and gravelly sand (glacio-fluvial) over impermeable glacial loam ("diluvium")

additional arguments confirming the "diluvial" character of loams forming the base of hill Senitzeberg, such as moraine pavement layer at the contact between loams and overlying sands, with occasional ventifacts. In author's opinion, the hill is a remnant of a sandy esker created at the deglaciation of the continental ice-sheet. The greatest depth of the sands (exceeding 2.5 m) was found in the central and eastern parts of the hill. Kraut believed that the loams occurring almost on the ground surface between the present street Wschodnia and the railway track are of alluvial genesis, even though they are in immediate contact with boulder loams that build the base of the esker. An important result of that work was the documentation of the large thickness of humus horizon in some soils of the station, exceeding 50 cm, and locally attaining 100 cm.

The hydrogeological survey conducted in the years 1964–1965 by a team headed by Mazij [Mazij et al. 1965] covered a small sector of fields immediately neighbouring the Agro- and Hydrometeorological Observatory, but it involved a large number of pits and drillings down to as much as 8 m, thus it provided a lot of new data for the interpretation of the genesis and spatial variability of the sediments. First of all, it was demonstrated that beneath the sands in the Siennickie Hill there is not one but two layers of loams (brown loams and grey loams), usually separated by glaciofluvial sands (Fig. 10). The lower loam occurs over the entire area covered by that survey, while the upper one thins out and locally disappears. In such places, its former presence is evidenced only by the pavement stones between the different layers of sand. In this case, the Holocene alluvial sands are deposited directly on glaciofluvial sands, and the combined thickness of the sands (to the contact with grey loam) may reach 8 m. It was demonstrated that the groundwater table varies seasonally from 0.65 to 1.4 m BGL.

The detailed map (1:25.000) published in the Geological Atlas of Wrocław [Buksiński et al. 1974] identifies an "island" of boulder loams of the maximal stage of Central-Polish glaciation (Odra glaciation) in the central part of the AES Swojec, but does not mention that loam as being covered by any sand (Fig. 11).

Thick glaciofluvial sands were identified, but – which is surprising – on the south-western edge of the loam island, i.e. at the intersection of streets Wschodnia and Bartnicza. The map identifies also river sands of the Pleistocene terrace (III) on a small isolated hill in the eastern part of the AES. Those sands overlie boulder loam of the Central-Polish glaciation that is positioned over boulder loam of the South-Polish glaciation (Fig. 12). Eastern part of the AES, around the hill, is covered by the alluvial sands and loams of the upper fluvial terrace (II) underlain by loam of the Central-Polish glaciation. The northern and western parts of the AES are built of river sands of Holocene upper fluvial terrace (II), deposited directly on boulder loam of the South-Polish glaciation (Fig. 11), which clearly indicates the disappearance of the loams of the Central-Polish glaciation in that site – at least partly in agreement with the conclusions of Mazij et al. [1965].

In view of the above data, the Detailed Geological Map of Poland (1:50.000) was considered useless for local analyses, as it excessively generalises the geological structure of the area. Contrary to other, more detailed surveys, that map delineates the loams over sands at the Siennickie Hill, omits the occurrence of fluvioglacial sands on the surface, and indicates sands of Pleistocene terrace (III), theoretically presently non-flooded, to

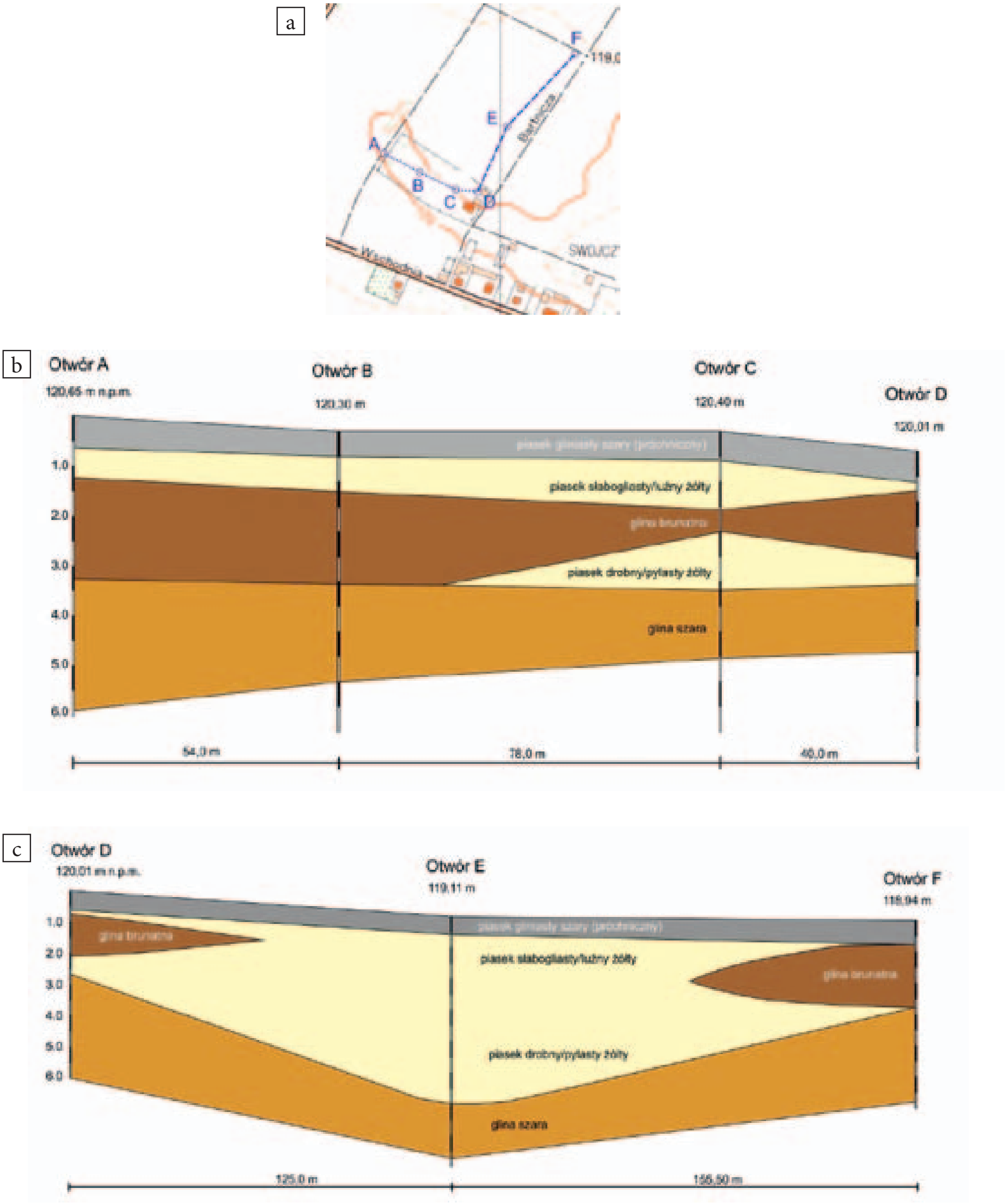


Fig. 10. Geological cross-sections of the sediments in the vicinity of the meteorological station [based on Mazij et al. 1965, simplified]
a – schematic layout of drillings and sections, b – section ABCD, c – section DEF

Fig. 11. Geological structure of settlements Swojec and Strachocin according to the Geological Atlas of Wrocław [Buksiński et al. 1974]
Legend: 2 – silts, sands and gravels with organic residues in river valleys – Holocene lower fluvial terrace (I), 3 – humous alluvial sediments of Holocene upper fluvial terrace (II), 4 – loams, sands and gravels of upper fluvial terrace (II), 5 – alluvial loams, sands and gravels over boulder loam of South-Polish (San) glaciation, 8 – river sands and gravels of Pleistocene terrace (III), presently non-flooded, 10 – boulder loam of Central-Polish (Odra) glaciation, 13 – sands and glaciofluvial gravels of Central-Polish (Odra) glaciation

the south and west of the Siennickie Hill, in areas completely covered with water during the great floods of 1903 and 1997 (Fig. 13).

In the years 2001–2004, the group headed by prof. T. Chodak conducted a pedological survey in the western part of the AES. The survey included of about 40 soil pits and over 50 drillings to the depth of 1.5 m. That survey confirmed the following:

- the alluvial character of sands forming the surface layer of all the soils except for those on the Siennickie Hill;
- the common occurrence of moraine stone pavement, including ventifacts, at the contact between alluvial sands and underlying loams, or alluvial sands and underlying sands of other genesis;
- the common occurrence of moraine stone pavement separating sands also on the Siennickie Hill, which suggests the presence of alluvial sand of Pleistocene terrace overlying the older glaciofluvial sands;

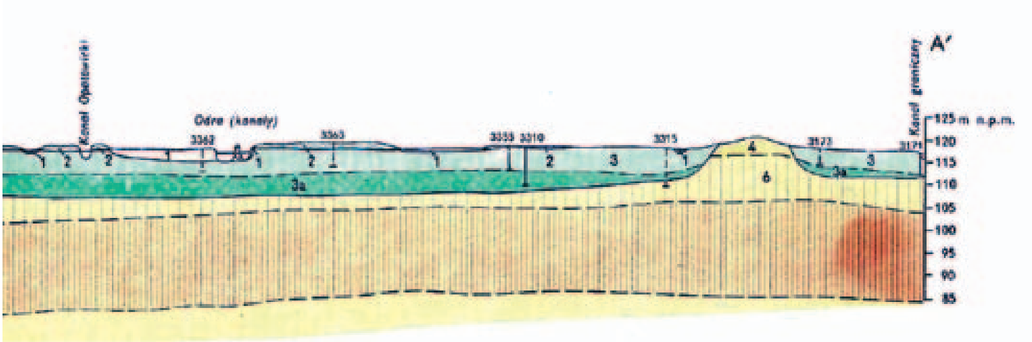


Fig. 12. Geological structure of settlements Swojec and Strachocin on the section from the Odra to the Graniczny Canal [Buksiński et al. 1974]
Legend: 1 – peats, silts, sands with organic residues in river valleys – Holocene lower fluvial terrace (I), 2 – alluvial homous sediemnts of Holocene upper fluvial terrace (II), 3 – fluvial loams and sands with gravel; gravel in the floor, 3a – sediments of terraces II and III, unseparated, 4 – fluvial sands and gravels of the Pleistocene terrace (III), presently non-flooded, 6 – boulder loam of Central-Polish (Odra) glaciation, 6 – boulder loam of South-Polish (San) glaciation

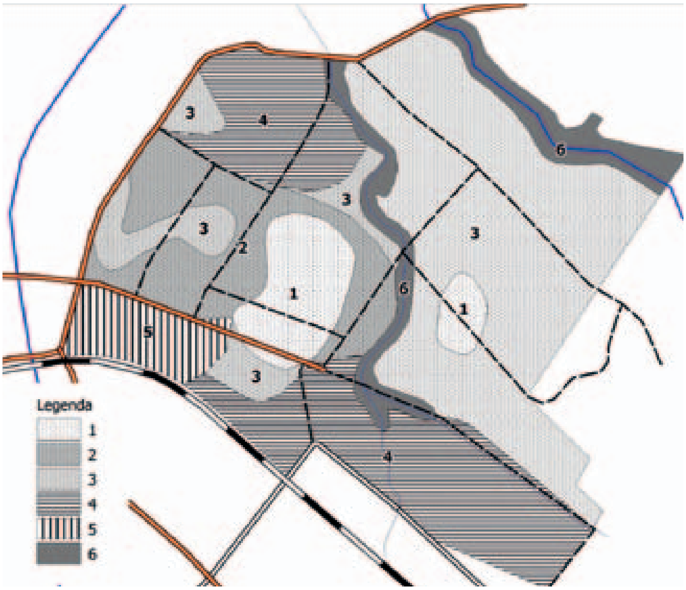


Fig. 13. Geological structure of the area of AES Swojec (surface sediments) – a synthesis
Legend: 1 – fluvial sands of Pleistocene terrace III over glaciofluvial sands, 2 – fluvial sands of Holocene upper fluvial terrace II overlying the moraine loam of the Odra glaciation, 3 – fluvial sands of Holocene upper fluvial terrace II over glaciofluvial sands overlying the moraine loam of the San glaciation, 4 – fluvial loams over sands of the Holocene fluvial terrace II, 5 – sandy loams of terrace II (Holocene) on moraine loam of the Odra glaciation, 6 – strongly humic loams and fluvial sands of lower fluvial terrace I, flooded

- the glacial and not the alluvial origin of loams in the area between street Wschodnia and the railway track.

This recognition is largely in agreement with the results of the survey by Mazij et al. [1965], but it allows to extend the conclusions over the entire area of the AES, and thus to integrate the results of pre-war and post-war studies.

7.1.2. Geological structure in the area of the Agro- and Hydrometeorological Observatory

The Observatory is situated at the foot of the Siennickie Hill, on the upper fluvial terrace (II). The deeper substrate is built of glacial loam (grey, strongly stony) of the San glaciation, extending up to the depth of 2.7–3.3 m BGL (Fig. 10b) or to 5–6 m BGL in some places (Fig. 10c). Due to their cohesion and impermeability, those loams are considered to be a barrier for groundwater. Grey loams are overlain by brown loams of the Odra glaciation. These brown loams have a thickness 0.5–2 m (in the western part of the Observatory) and extend up to the depth of 0.85 to 1.6 m BGL. However, in some places, the brown loam wedges off until it disappears completely (Fig. 10 c). In the western part of the area, loams of the San and Odra glaciations do not contact directly, but they are separated by glaciofluvial sands (at a depth of 2–3 m below ground level). Somewhat to the north from the Observatory (Fig. 26), in a distinct trough eroded in the San loams, above which the Odra loams have disappeared, the glaciofluvial sands fill the "trough" and attain the total thickness of up to 5 m and are saturated with water throughout their volume. Therefore, the brown (upper) loam of the Odra glaciation can be saturated both with precipitation water infiltrating from the soil surface and with groundwater, through capillary rise from underlying sands saturated with water. At the ground surface, over the loams of the Odra glaciation, the Holocene fluvial sands were deposited thus creating the upper fluvial terrace (II). The sands are layered, weakly humic in the surface part, and often saturated with water, thus strongly gleyed.

Therefore, the area of the Agro- and Hydrometeorological Observatory has a relatively homogeneous geological structure of Quaternary sediments; although the variable upper relief of the brown glacial (Odra) loams and the variable thickness of the surface fluvial sands have a differentiating effect on the soil moisture conditions of the area. It should also be emphasised that the intensity and direction of drainage of the surface sands are affected not only by the lowering of the subsurface loam to the north, but also by the artificial drainage (pipes) that drains the area of the Observatory both from the north and from the south.

7.2. Typology and chemical properties of soils in the area of the Agro- and Hydrometeorological Observatory

The Agro- and Hydrometeorological Observatory is situated entirely on the Holocene upper fluvial terrace with predominant sandy sediments. These are fine-grained loamy sands in the surface layers, with deep changing to loose sands, and having thin interlayers of loamy sand and sandy loam, less frequently gravelly sands (Tab. 1). The surface sandy layer has a total thickness of 80–90 to over 150 cm and is the thinnest in the western part of the Observatory, while the thickest – in the north and east from the Observatory. The Holocene fluvial sands are underlain by glacial loam that has a texture class of sandy loam or loam (Tab. 1). As shown by geological probing, the underlying layer of boulder loam has a variable total thickness and very variable relief of its upper contact. Locally, the loam (the so-called upper loam) disappears completely, and then the soils have sandy texture throughout their profiles. The presence of underlying loam and the depth of the sand/loam contact inflence the moisture conditions in the soils. The soils can be influenced by both the ground water connected with the river systems of the Widawa and Odra (at high water levels in the rivers), and by waters periodically stagnating above the impermeable loam. Irrespective of the origin of the saturating water, the soils are fully saturated with water below the depth of 100–120 cm for several months in a year. Seasonally, the saturation with water can reach the depth of 50–70 cm BGL, or even higher. However, these situations are short lasting, as the artificial drainage system installed at the depth of about 70 cm rapidly removes the moisture excess and decreases the water table at least below 70 cm BGL. The water saturation in the bottom part of soil profile results in reductive conditions and the development of strong reductomorphic (gley) features. In the middle part of the profile the reductomorphic features are weakly or medium pronounced and change to oxymorphic features, i.e. rusty spots and iron-manganese intrusions, which reflects the seasonal variability of the water-air conditions in that part of the profile.

Table 1

Particle size distribution of the proper alluvial soils
(texture fractions and classes according to classification PTG 2008)

Profile	Horizon	Depth	Percentage share of fraction with diameter [mm]									PSD group
		[cm]	>2	2.0– –1.0	1.0– –0.5	0.5– –0.25	0.25– –0.1	0.1– –0.05	0.05– –0.02	0.02– –0.002	< 0.002	
3M	Ap	0–28	0	2	8	23	42	8	8	7	2	pg (dr)
	AB	28–39	0	1	9	24	43	6	10	6	1	pg (dr)
	Cgg1	39–77	0	2	9	20	48	11	6	3	1	ps (dr)
	Cgg2	77–106	0	2	16	33	43	2	2	1	1	pl (śr)
	Cgg3	106–122	2	4	17	23	42	3	1	1	9	pl (dr)
	2G	122–150	2	1	5	18	35	7	7	9	18	gp (dr)

Explanation:

pg – piasek gliniasty – loamy sand, ps – piasek słabogliniasty – sand (finer),
pl – piasek luźny – sand (loose), gp – glina piaszczysta – sandy loam, (dr) – drobnoziarnisty – fine-grained,
śr – średnioziarnisty – medium-grained

Table 2

Morphology of the proper alluvial soil (gleyed) – soil pit No. 3M
FAO-WRB 2015: Eutric Fluvic Brunic Endogleyic Arenosols (Aric)

Symbol and depth of horizon [cm]	Description of horizon
Ap 0–28	grey-brown (10YR 4/2) arable-humus horizon with particle size distribution of loamy sand (small-grained), skeleton-less; medium-stable aggregate structure, medium coarse; loose structure; fresh moisture; no spots and redoxymorphic intrusions; distinct uniform transition
AB 28–39	brown (10YR 4/3) transitional horizon with traits of browning with particle size distribution of loamy sand (small-grained), skeleton-less; stable aggregate-subangular structure, medium-coarse; loose-compacted structure; fresh moisture; infrequent Fe-Mn intrusions; gradual transition
Cgg1 39–77	light-grey (2.5Y 7/3) parent rock horizon – weakly loamy fluvial sand (small-grained), skeleton-less, no visible stratification; separate-grain structure, loose; fresh moisture; ca. 20% of surface covered with rusty oxymorphic spots and Fe-Mn intrusions; gradual transition
Cgg2 77–106	yellow-brown (10YR 6/7) loose sand (medium-grained), skeleton-less, no visible stratification; separate-grain structure, loose; fresh moisture; ca. 30% of surface covered with rusty oxymorphic spots and soft Fe-Mn concentrations; gradual transition
Cgg3 106–122	light-grey (2.5Y 7/2) loose sand (small-grained), with individual intrusions of small gravel; separate-grain structure, loose; moisture status: wet; zonal gleying, numerous soft concentrations of Fe-Mn; distinct transition, mottled
2G 122–150	grey-brown (2.5Y 6/2) (fine-)sandy loam, very poor skeleton; cohesive structure, semi-plastic; moisture status: wet; strong spotty gleying (dominant reductomorphie stains) and numerous soft ferrous intrusions

According to typological soil classification, the proper alluvial soils (PL: mady właściwe) that are typical soils of river valleys [Kabała et al. 2015], dominate in the area of the Agro- and Hydrometeorological Observatory (Tab. 2). In their profile, the following soil horizons were distinguished: the arable-humus horizon Ap (thickness of 26–45 cm, grey or grey-brown colour, Munsell 10YR 4/2–4/3), followed by the sideric horizon Bv (or transitional horizon ABv) reaching down to 50–60 cm, overlying the pedologically unchanged, stratified and gleyed sand (horizons Cgg or G). The presence of the sideric horizon Bv (which is an analogue of brown horizon in sandy soils) indicates transformation processes of high intensity, progressing down the soil profile because of soil drainage and increased biological activity of aerated layers. The arable-humus horizon contains ca. 1% of organic carbon (ca. 1.7–2% of humus) and has acidic or weakly acidic reaction, which is connected with relatively low saturation with base cations (in the range of 45–60%). Both the pH of the soil and the content of exchangeable base cations (as well as base saturation) increase down the soil profile and attain the highest values at the contact with the underlying loam. The soils are characterised by medium content of available forms of phosphorus, potassium and magnesium (Tab. 3). Due to the dominant sandy texture, the soils have generally low agricultural value, that is exemplified by the IVb bonitation class and 5 or 6 agricultural suitability complex (soils suitable for rye production). In the international classification FAO-WRB (IUSS 2015) the soils are classified in the reference group of Arenosols [Eutric Fluvic Brunic Endogleyic Arenosols (Aric)].

Table 3

Basic chemical properties of the proper alluvial soil (gleyed) – soil pit No. 3M

Profile	Horizon	Depth	pH_{H2O}	pH_{KCl}	C_{org}	N_{tot}	C:N	P_a	K_a	Mg_a
		[cm]			[%]			[mg·kg^{-1}]		
3M	Ap	0–28	4.8	3.8	0.97	0.08	12	63	115	70
	AB	28–39	5.5	4.5	0.72	0.07	10	30	62	42
	Cgg1	39–77	6.4	5.3	0.47	<0.03	-	24	55	17
	Cgg2	77–106	6.8	5.7	0.12	<0.03	-	18	48	20
	Cgg3	106–122	7.2	6.1	0.14	<0.03	-	3	22	23
	2G	122–150	7.5	6.2	0.21	<0.03	-	12	26	41

Also, the anthropogenic soils with an arable horizon at least 50 cm thick, developed through deep mixing (ploughing) of the surface layers of the original alluvial soils (rigosols) occur in the western part of the Observatory and in the surrounding area. They have a texture of loamy sand changing with depth to (loose) sand and underlain by loam at various depth, similarly to the neighbouring proper alluvial soils. The arable horizon of the rigosols has a slightly acidic reaction, humus content within the range of 1–2%, and a low value of the C:N ratio. Base saturation is very high throughout the profile, from 75% in the surface layers to 90–95% in the bottom layers. Due to intensive mineral fertilisation, the content of available P, K and Mg forms in the arable horizon attains high and very high values. However, the general quality of those soils oscillates around class IVb, which is related to their thick, structural and nutrient-rich arable horizon that compensates for their sandy texture. This corresponds with the complex 5 of agricultural suitability (so called good rye complex). According to an international system WRB (IUSS 2015), rigosols in the observatory area, having preserved alluvial features, are classified as Phaeozems [Fluvic Gleyic Phaeozems (Anthric, Arenic)].

7.3. Physical and water properties of soils in the area of the Agro- and Hydrometeorological Observatory

The proper alluvial soils and the rigosols developed from alluvial sediments, situated in the area and vicinity of the Agro- and Hydrometeorological Observatory, have in their surface horizons, the physical and water properties typical for sandy soils, which is reflected in the values measured in profile 3M (Tab. 4 and 5).

The specific density is close to the density of pure quartz (approx. 2.65 g·cm^{-3}) only in the bottom layers of the profile (poor in organic matter), while in the surface horizons the admixture of organic matter reduces the soil density to 2.54–2.55 g·cm^{-3}. Also the bulk density (determined with the thermo-gravimetric method in soil samples with undisturbed structure taken into steel cylinders with a volume of 100 cm^{3}) is the lowest in the surface layers, where it oscillates around 1.4 $g\cdot cm^{-3}$. The bulk density in the deeper horizons increases gradually to 1.55–1.58 $g\cdot cm^{-3}$, which indicates moderate compaction of the layers. The total soil porosity, calculated on the basis of specific and bulk densities, oscillates in the range of 40–45% and attains the maximum in the arable-humus horizon. The lowest total porosity was found in the deepest layer of loamy sand, which results from the relatively greater compaction of that layer. The capillary porosity, identified with the maximum actual water capacity of capillary pores, is lower than the total porosity, assuming values in the soil under study within the range from 30 to 40%. Opposite to the total porosity, the highest capillary water capacity is noted in the soil with the finest (loamy) texture, and not in the surface humus horizon. This means that in the sandy surface layers a notable part of the total porosity (up to 10%) is accounted for the non-capillary pores with poor water retention capacity. The water permeability (identified with the filtration coefficient in the saturated zone) is relatively high in the surface sandy layers, where it attains values from $2.9\cdot10^{-3}$ to $4.6\cdot10^{-3}$ $cm\cdot s^{-1}$ and is lower by an order of magnitude in the more compacted underlying layers, both sandy and loamy. The lowest value of the filtration coefficient, $1.88\cdot10^{-4}$ $cm\cdot s^{-1}$, was found in sandy loam at the depth of 120–150 cm BGL.

Table 4

Physical and water properties of the proper alluvial soil (gleyed) – soil pit No. 3M

Profile	Horizon	Depth of horizon	Specific density	Bulk density	Total porosity	Hydraulic capacity		Hydraulic permeability
						field	capillary	
		[cm]	[$g\cdot cm^{-3}$]	[$g\cdot cm^{-3}$]	[%]	[%]	[%]	[$cm\cdot s^{-1}$]
3M	Ap	0–28	2.54	1.39	45.3	12.5	36.9	$4.56\cdot10^{-3}$
	AB	28–39	2.55	1.41	44.5	12.2	36.2	$2.90\cdot10^{-3}$
	Cgg1	39–77	2.56	1.46	43.0	10.2	33.1	$4.10\cdot10^{-3}$
	Cgg2	77–106	2.60	1.53	41.1	6.0	30.2	$4.66\cdot10^{-4}$
	Cgg3	106–122	2.63	1.58	39.9	24.4	32.6	$2.39\cdot10^{-4}$
	2G	122–150	2.65	1.55	41.5	31.1	39.5	$1.88\cdot10^{-4}$

Table 5

Water capacity of the proper alluvial soil (gleyed) – soil pit No. 3M at specific pF values

Profile	Horizon	Depth of horizon	Water content [% $cm^3\cdot cm^{-3}$] at pF value									
		[cm]	0	1	1.5	1.8	2.0	2.3	2.54	2.7	2.9	4.2
3M	Ap	0–28	36.9	34.0	25.3	14.8	12.5	10.2	9.7	9.3	8.9	1.4
	AB	28–39	36.2	33.6	25.3	14.6	12.2	10.1	9.6	9.2	8.8	1.4
	Cgg1	39–77	33.1	31.8	24.1	13.0	10.2	8.3	7.7	7.3	6.9	1.0
	Cgg2	77–106	30.2	26.7	19.2	7.6	6.0	4.5	4.1	3.7	3.4	1.1
	Cgg3	106–122	32.6	30.2	28.1	26.0	24.4	22.8	21.9	21.3	20.8	3.7
	2G	122–150	39.5	37.9	34.3	32.2	31.1	28.8	27.3	26.2	24.9	5.2

The field water capacity (FWC), determined at soil water potential equivalent pF = 2, is very low, within the range of 6–12.5% $cm^3 \cdot cm^{-3}$. This indicates very low water content in the range most favourable for plant vegetation, as well as the dependence of crop yielding on the groundwater level and on the weather conditions. In the sandy horizons, somewhat higher values of FWC occur in the arable horizon, which results equally from the higher content of the clay fraction and from higher humus content. Significantly higher FWC was measured in the horizons with particle size distribution of loamy sand (about 25% $cm^3 \cdot cm^{-3}$) and sandy loam (ca. 31% $cm^3 \cdot cm^{-3}$), but this is of lesser practical importance due to common saturation with groundwater at these depths. Table 5 presents the results of detailed measurements of soil moisture at specific values of soil water potential within the range of pF 0–4.2 (permanent wilting point of plants), that can be used for the calculation of all the indices of the amount of water available for plants (resources of usable water) in the soil profile.

8. Agrometeorological conditions in the years of the experiment

Information on the weather conditions in the course of the field experiment is a highly important factor as their variation largely affected the vegetation of all the energy crops involved in the study. The biometric measurements of the energy plants included in the experiment were started when the plants reached the height of at least 0.5 m. That height was an index value obtained on the basis of observations conducted by the authors of this work. Observations conducted during the three years of the experiment indicated that the index height was attained by the shoots of the energy plants at times in various periods of the month of May. Hence, the characterisation of the weather conditions in the periods of their vegetation was performed for decade (10/11-day) periods, starting from the 1st decade of May and continued to the 3rd decade of October, when the final biometric measurements were made in the years 2011–2013. The multi-year period of 1971–2000 was adopted as the normative period to which the values of the selected meteorological elements from the particular years of the experiment were referenced. The characterisation of the thermal conditions was conducted on the basis of the standard recommended in Poland by the IMGW-PIB, while the precipitation conditions were characterised on the basis of the classification by Kaczorowska [1962]. The estimation of the groundwater table levels in the years selected for the analyses was conducted with relation to the normal levels in accordance to the study by Biniak-Pieróg [2014] based on the normal multi-year period of 1971–2000. Figure 14 presents the mean multi-year sums of precipitations and normative values of groundwater table levels from the period of 1971–2000 in the area of the Observatory.

The characterisation of weather conditions in the period of the field experiment was performed for several commonly used meteorological elements. Table 6 presents the decade values of air temperature, atmospheric precipitations and groundwater levels against the background of values from the multi-year period of 1971–2000 adopted as the reference. Based on the mean decade air temperatures and their deviations from the multi-year values, the analysed vegetation seasons in the years of the experiment can be classified as warm every time. In the years 2011 and 2012 warm and very warm decades dominated, while in 2013 – very warm. This characterisation would be incomplete as the decade is a relatively long period of time. Therefore, the formulation of conclusions on air temperature conditions would be too limited and not fully reflecting the information on the vari-

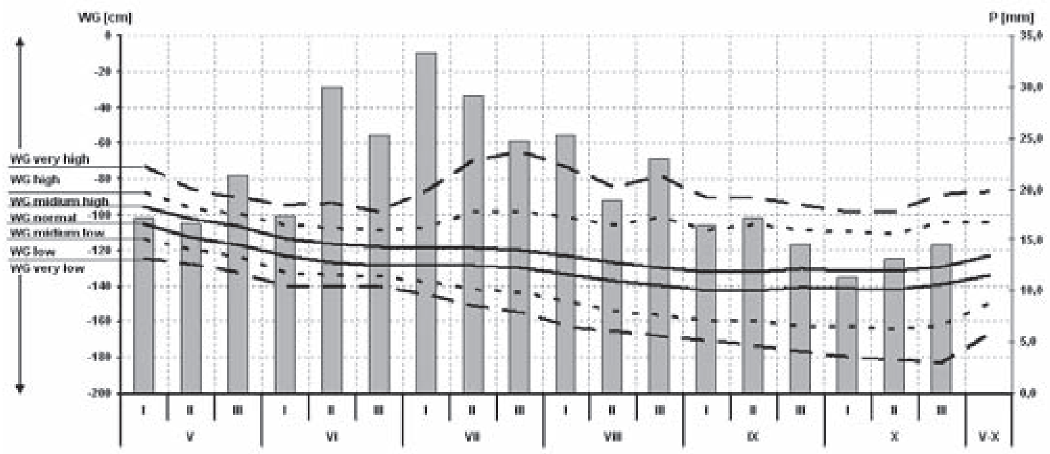


Fig. 14. Mean multi-year sums of atmospheric precipitations P and normative levels of groundwater table WG from the period of 1971–2000 in the area of the Agro- and Hydrometeorological Observatory UELS in Wrocław-Swojec

ation of that meteorological element in the course of the individual vegetation periods. The presentation of the thermal conditions is fuller when complemented with information on the extreme values and the frequency of their occurrence within a vegetation season. For this reason it was decided to analyse, for the periods from the beginning of May to the end of September, the number of days – and frequency of their occurrence – with maximum diurnal temperature above 25°C, classified as hot weather days, and with maximum temperature above 30°C – classified as boiling hot. October was not taken under consideration due to the fact that only in 2011, in the first decade, i.e. on the 1st and 4th, the maximum temperature was 25.0 and 25.8°C, respectively. In the other years the maximum values of air temperature in that month did not exceed the threshold of 25°C. According to this classification, in 2011, in the period from May to the end of September, there were 58 hot days, which constitutes ca. 38% of the period in question. The largest number of those days were noted in the second decade of July – 8. In the period from May to September the number of days with that temperature level varied from 10 to 7 in the particular months. The coolest was the first decade of May, when for three days, from the 4th to the 6th of May, the minimum air temperature was below 0°C. Only 5 sweltering hot days were recorded. Two such days were on the 5th and 6th of June, one on the 17th of July, and the remaining two on the 26th and 27th of August. Relative to the entire five-month period those instances constituted 3.27%.

The year 2012 was somewhat different as the noted number of hot days during the five-month period was 39, which constituted ca. 25 % of the period in question. The structure of the number of those days was similar to the preceding year only in May and July, with the number of such occurrences being 9 and 13, respectively. In June there were only 5, in August 10, and in September only 2 such days. Whereas, the number of boiling hot days was three-fold higher than in the preceding year, with 15 such days. The first occurred on the 1st of May, another three were the 16th, 18th and 30th of June. The next five days with such maximum air temperature were noted in July. Three of them in the first decade, and the other two in the third. Five more boiling hot days were noted in August – three in the first and two in the second decade. The last such occurrence took place on the 11th of September, when the maximum recorded air temperature reached the level of 30.4°C. In total, boiling hot days constituted 9.8% of the whole period under discussion. That was three-fold more of such occurrences than in the preceding year.

The year 2013 was somewhat similar to the preceding year with regard to the structure of hot and boiling hot days, the numbers of which were 32 and 13, respectively. In total, the hot and broiling hot days accounted for 20.9 and 8.5%, respectively, of the whole period in question. In May five days classified as hot were noted – two in the first and three in the second decade. In the period from the third decade of June to the first decade of July the highest value of air temperature was noted on the 8th of July – 24.1°C, while the lowest – 13.1°C on the 24th of June. In the second and third decades of June five hot days were recorded – 2 and 3, respectively. Compared to the preceding years, July 2013 proved to be richer in hot days as the noted number of such days was 16, which amounted to a half of all the days in the course of the five months under analysis. There were 6 such days each in the first and third decades. In August there were 5 hot days, four in the first and one in the second decade. In the last of the months under analysis only on the 8th of September air temperature of 26.3°C was recorded. Compared to the other years, that was the smallest number of hot days in that month. There was a series of boiling hot days in 2013. Three such days were noted in the period from the 18th to the 20th of June, with maximum temperatures of 31.5, 30.3 and 33.1°C, respectively. Another 9 boiling hot days occurred in the period between the 26th of July and the 8th of August. After a period of lower maximum temperatures, only on the 18th of August the maximum temperature reached the value of 30.3°C. This information demonstrated the diversity of temperature conditions of the particular years in which the vegetation of the energy crops proceeded.

Another meteorological element and the most important from the viewpoint of water acquisition is atmospheric precipitation. Figure 15 presents percentage deviations of precipitations in the years 2011–2013 from the values for the multi-year period of 1971–2000 adopted as the norm. The rainfall conditions of the entire summer half-years covering the periods of growth of the energy crops in the field experiment corresponded to the wet periods in the years 2011 and 2012 (453.8 and 427.6 mm, respectively), while the same period in 2013, with precipitation sum of 541.3 mm, was classified as very wet. In 2011, during the vegetation of those plants very wet decades dominated, while in 2012 wet decades were observed most frequently. Most often the occurrence of decades with above-normative precipitations was observed after decades with low precipitation. The year 2013 was different, with extremely wet and wet decades being observed most abundantly.

Like in the case of the analysis of air temperature conditions, the variation of decade sums of precipitations in relation to the multi-year values does not present a full picture of the influx of water from precipitation, and thus also the potential possibility of its use by the energy crops. This results from the fact that the decade sum of precipitation does not always mean precipitations distributed uniformly during the decade. Very often the diurnal precipitations are cumulated, occurring on consecutive days, or they appear in large abundance over a short period of time, and in such a situation their potential usefulness for plants is varied. Irrespective of the sums of precipitation for any time interval, atmospheric precipitation is also characterised by the number of days with its occurrence. That factor carries highly valuable information, as it permits the estimation of the time, days in this case, in which an influx of precipitation water to the ground takes place. Analysing that element for long time intervals, e.g. summer half-years or vegetation seasons, one can observe its moderate variation in the particular years. In the consecutive years of the field experiment conducted by the authors the number of days with atmospheric precipitation varied. In the summer half-year of 2011 the number of days with precipitation was 75, in 2012 – 93, while in 2013 – 88. The observations of vegetative activity of the crop plants, made in the course of the experiment, permit the statement that October precipitations have only an insignificant effect on their growth. Whereas, precipitations at the start of vegetation are important due to the progressing development of the plants. Taking that fact into account, a comparison was made between the number of days with precipitation in shorter time intervals, i.e. the particular months in the consecutive years. In May 2011 the number of days with atmospheric precipitation was 9, and in May 2012 – 7. May 2013 was drastically different in this respect, with 19 days with precipitation. June was fairly uniform, as the numbers of days with precipitation in the consecutive years were 15, 17 and 16, respectively. Another variation of that index can be observed in July, when the highest number of days with precipitation was characteristic of 2012 – 23 days, while the lowest number of days with precipitation was noted in 2013 – 14. August, similarly to June, was little varied in this regard. In 2011 there were 13 days with precipitation, in 2012 – 14 days, and in 2013 – 11 days. September was notably varied in the consecutive years. In 2011 in that month 6 days with precipitations were noted, in 2012 that number increased to 11, and in 2013 to as many as 17 days. The numbers of days with precipitation complements the knowledge on atmospheric precipitations, but does not provide information on what kind of precipitations we were dealing with, similarly to the sums of precipitations in specific time intervals. It is the value of the diurnal sums of precipitations that allows the estimation of their effectiveness. The analysis of the diurnal sums of atmospheric precipitations revealed their notable diversity. Due to the fact that, as a rule, precipitations with diurnal sums are little effective, special attention of the authors was focused on diurnal sums higher than 10.0 mm per day. In 2011 there were 13 such occurrences in the summer half-year, in 2012 – 12, and in 2013 as many as 18. The combined sum of precipitations obtained from the presented diurnal sums was 283.7 mm in 2011, in 2012 – 255.7 mm, and in 2013 – 410.5 mm. Comparing those sums to the sums for the whole summer half-year, counted from May to the end of October, one can note that in 2011 the sum of precipitations formed from the 13 diurnal sums constituted 62.5%, in 2012 – 59.8%, while in 2013 that percentage value was as much as 75.8%. Whereas, analysing diurnal sums higher than 15.0 mm per day, in the consecutive years of the experiment they were noted as follows: in 2011 – 10 days, in 2012 – 8 days and in 2013 – 14 days. Those precipitations were intensive in character, short-lasting, therefore a major part of the water could not penetrate into the soil profile and was turned into surface runoff. The above brief characterisation of atmospheric precipitations during the period of the field experiment provides an image of the potential possibilities of utilisation of the atmospheric precipitation water by the energy crops.

Table 6

Decade values of air temperature tp, atmospheric precipitations P and groundwater table level below ground level Wg in the years 2011–2013 in Wrocław-Swojec

Month	V			VI			VII			VIII			IX			X		
Decade	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
tp [°C]																		
1971–2000	12.2	14.4	14.6	16.6	15.9	17.2	18.0	18.3	18.7	19.1	18.3	16.4	15.0	13.3	12.4	11.0	9.2	6.6
2011	10.2	16.0	17.9	20.5	18.6	18.2	18.1	20.3	16.4	19.3	19.4	19.2	16.7	15.8	13.9	13.1	7.2	7.9
2012	16.1	13.1	18.0	14.4	18.5	18.8	22.4	17.4	20.2	20.3	18.0	19.5	16.6	14.2	12.9	11.3	9.3	5.4
2013	15.2	15.9	12.9	15.2	20.8	16.9	20.6	18.7	22.0	23.1	17.9	16.3	15.8	12.6	10.2	8.6	10.4	13.1
P [mm]																		
1971–2000	17.2	16.5	21.4	17.4	29.9	25.3	33.3	29.1	24.7	25.2	18.9	23.0	16.4	17.1	14.6	11.3	13.1	14.5
2011	20.3	17.4	11.7	33.4	3.1	59.2	54.7	34.7	81.5	14.1	34.9	15.8	26.9	3.5	0.0	15.0	23.3	4.3
2012	49.2	6.5	8.0	25.7	59.5	9.5	42.8	38.5	26.7	37.6	8.7	26.9	1.3	48.0	3.3	5.7	16.8	12.9
2013	71.9	14.0	50.0	74.1	0.0	97.6	2.7	16.0	17.6	45.8	16.5	5.9	12.1	70.2	23.5	0.4	6.0	1.4
Wg [cm]																		
1971–2000	-102	-109	-113	-119	-122	-124	-124	-123	-124	-127	-131	-134	-137	-137	-136	-137	-137	-132
2011	-119	-122	-127	-134	-138	142	-123	-116	-79	-90	-94	-110	-118	-119	-127	-134	-133	-131
2012	-117	-124	-140	-153	-154	148	-149	-143	-148	-155	-158	-162	-165	-160	-153	-158	-163	-162
2013	-60	-68	-96	-61	-62	56	-80	-102	-116	125	-130	-136	-143	-129	-97	-106	-115	-122

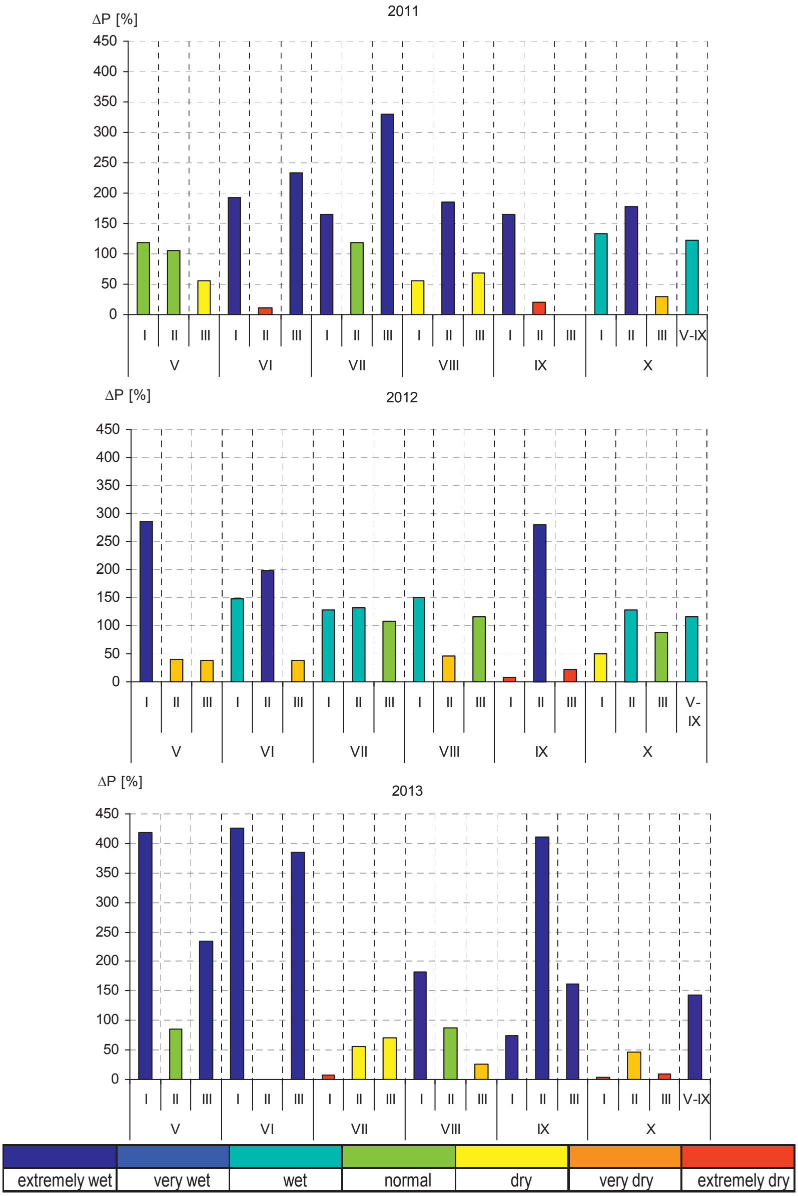


Fig. 15. Deviations ΔP [%] of decade sums of atmospheric precipitations from normal values for the period of 1971–2000 at the Agro- and Hydrometeorological Observatory WUELS in Wrocław

The next agrometeorological element under analysis was the level of groundwater table in the area of the experiments. The depths of the groundwater table in the summer half-years

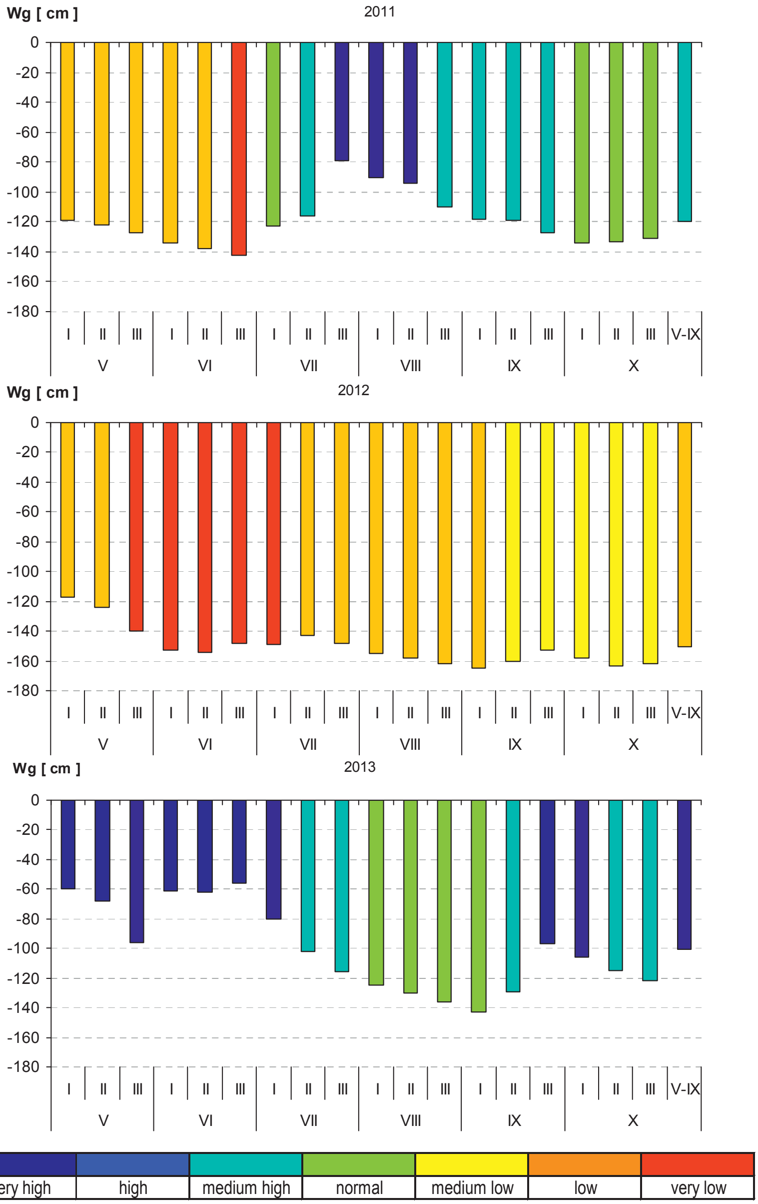


Fig. 16. Classification of mean decade states of groundwater table – Wg [cm] in the years 2011–2013 in relation to the values for the multi-year period of 1971–2000 at the Agro- and Hydrometeorological Observatory WUELS in Wrocław

of the consecutive years adopted for the analyses varied notable and amounted to, on average, -120 cm in 2011 (classified as medium high), -151 cm (classified as low) in 2012, and -122 cm (classified as high) in 2013. Figure 16 presents the classification of the decade states of groundwater table in relation to the normal values for the multi-year period of 1971–2000. Detailed analysis of the mean decade depths of groundwater table in the particular years revealed that in 2011, starting with the 1st decade of May until the 3rd decade of June a steady lowering was observed, from -119 to -142 cm, which corresponded to low and very low states. In the period from the 2nd decade of July to the 3rd decade of September the groundwater table states were medium high and high, and then, until the end of October, the depth of groundwater table was at the level of normal states. Notably different were the mean decade states of groundwater table in the summer half-year of the 3rd year of the plantation – 2012. During the whole period the level of the groundwater table was below the normal states, with medium low and low states dominant until the 2nd decade of September, and in subsequent decades, until the end of October – low states relative to the normal values (Tab. 6).

In the 4th year of the plantation, 2013, for a major part of the summer half-year the groundwater table was at depths corresponding to very high, medium high and high states, from the 1st decade of May till the 3rd decade of July, and from the 2nd decade of September till the 3rd decade of October. At other times those depths corresponded to the normal states.

The analysis of the weather conditions during the vegetation periods of the energy crops in the consecutive years of the experiment demonstrated their diversity from the viewpoint of the runs of air temperature conditions, atmospheric precipitations, and groundwater table levels.

9. Results

The field experiments and the observation and measurement materials obtained permitted the estimation of the conditions of field evapotranspiration of the particular energy crops (giant miscanthus grass, Virginia mallow, basket willow and Jerusalem artichoke) in the course of three vegetation seasons under conditions of varied access to water. It was decided to find an answer to the question to what extent the process of evapotranspiration can be described by the estimation of the possibility of mathematical notations with various degrees of complexity. Energy crops evapotranspiration during vegetation was conditioned by the meteorological elements for various time intervals. The variation was based on the use of the day as the basic time interval, while analyses for longer periods consisted in the accumulation of information correspondingly to the duration of the time period. The longer periods were: the pentade, week periods resulting from the fact of conducting biometric measurements used in the analyses, decade periods, and ultimately the entire vegetation periods of the particular plants. Since the experiments and analyses of evapotranspiration were conducted in evaporimeters preventing the plants from using the ground waters, and in the second variant which permitted free use of that source of water supply, models were created separately for those two situations. To achieve the best and as simple as possible mathematical notations, mathematical models with various levels of complexity were constructed for the estimation of the variation of evapotranspiration of the particular energy crops. The estimation of the value of evapotranspiration of the energy crops studied was conducted with the use of the developed and preliminarily tested deterministic model; WSMT [Żyromski et al. 2012b]. That model required, as input data, information on the calculated reference evaporation or on measured evaporation from open water surface as reference parameters. For that purpose the “FAO–Penman–Monteith” formula was applied, as well as measurements of evaporation from open water surface made with the help of EWP 992, conducted in the area of the Agro- and Hydrometeorological Observatory in Wrocław-Swojec. Due to the complexity of the Penman formula, the “EVAPO” application was created for the determination of diurnal values of reference evapotranspiration (ET_0), understood as the value of evaporation from the surface of a lawn in full development, growing on a soil that ensures the optimum conditions of vegetation [Chieng et al. 2012]. The application permits the determination of the value of ET_0 for any point designated by means of geographic coordinates and altitude above sea level on the basis of diurnal values of air temperature, relative humidity deficit, wind velocity and relative insolation. The set of input data includes also variables with tabulated values, such as the psychrometric constant dependent on the altitude above sea level and atmospheric pressure, maximum water vapour pressure and the tangent of slope of saturated water vapour pressure dependent on temperature, radiation at the upper limit of the atmosphere dependent on the consecutive number of the day of the year, that in the application are determined automatically on the basis of given geographic information. The “EVAPO” application permits the performance of calculations that allow the analysis of variation of the value of evapotranspiration in years, as well as in individual months. For the testing of the values of the results obtained, calculations made on the basis of a 30-year string of meteorological data from the period of 1971–2000 were used to determine the values of evapotranspiration for Vancouver and for Wrocław-Swojec, and a sample analysis was performed with the use of that application [Chieng et al. 2012]. The software created and tested in that manner proved to be highly useful in the determination of the values of reference evaporation for the years 2011–2013, when the field experiment was conducted.

During the period of the study there occurred situations when the diurnal sums of precipitations notable exceeded the level of 10 mm per day. A total of 43 such instances were recorded during the entire three-year period of field measurements. Under natural conditions, excess of precipitation water which the soil cannot absorb flows off over the surface of the ground. Whereas, in the case of evaporimeters that is not possible and the surplus water stagnates unnaturally on the surface of the soil monolith. A part of the water stagnating on the surface of the soil monolith in the evaporimeter evaporates, and another part slowly infiltrates the soil. Such a situation causes that the measured changes in the weight of the evaporimeter at 24-hour intervals indicate erroneous information concerning the value of evapotranspiration. Therefore the information on the diurnal evapotranspiration from the particular evaporimeters raise numerous doubts. Taking this into account, it was decided to exclude values of evapotranspiration measured by means of the evaporimeters on days with diurnal sums of precipitation above 10 mm per day from the models with 24-hour time step.

9.1. The deterministic model

Calculations were made using model “WSMT” (the name of the model comes from the first letters of the energy crops selected for the study). The model permits the determination of the moving average of actual evapotranspiration on the successive days of vegetation on the basis of precipitation and evaporation from open surface of water measured with the evaporimeter EWP 992 or of the value reference evapotranspiration calculated from the formula derived by Penman–Monteith:

$$F(\alpha,\beta,\gamma,\theta,\delta,n)=\frac{1}{20}\sum_{\mathrm{i=n-19}}^{\mathrm{n}}ETR_i=\frac{\alpha}{20}\sum_{\mathrm{i=n-19}}^{\mathrm{n}}E_{0_i}+\beta+\frac{\frac{\gamma}{20}\sum_{\mathrm{i=n-19}}^{\mathrm{n}}P_i}{1+e^{\theta(n-\delta)}}$$

where:

ETR_i – actual evapotranspiration on the i-th day of vegetation,

$E_{0\mathrm{i}}$ – evaporation from open water surface on the i-th day of vegetation or reference evapotranspiration calculated from the “FAO–Penman–Monteith” formula,

P_i – value of atmospheric precipitation on the i-th day of vegetation,

n – n-th day of vegetation ($n \geq 20$),

$\alpha, \beta, \gamma, \theta, \delta$ – model parameters.

The values of the model parameters were determined by seeking the global minimum of a multivariate function defined as follows:

$$f = \sum_{n} \left(F(\alpha,\beta,\gamma,\theta,\delta,n) - \overline{F_n} \right)^2$$

where:

$\overline{F}_n$ – twenty-day moving average of actual evapotranspiration determined from the n-19 to the n-th day of vegetation.

That problem was solved with the help of the genetic algorithm proposed by Price et al. [2005].

The fitting of the model was performed for every set of data obtained from measurements with the soil evaporimeters for each of the plants under study in the consecutive years.

The results of calculations for the years 2011–2013 by means of the procedure of seeking the global minimum of the multivariate function for the energy crops under study, with the use of the measurements of actual evaporation from open water surface, measured with evaporimeter EWP 992, in the form of the model parameters in the particular years, are presented in Tables 7, 8 and 9. Whereas, Tables 10–12 present the model parameters obtained with the use of values calculated with the formula derived by Penman–Monteith. In this variant the calculations were made separately for each of 5 evaporimeters and the four energy crops. Due to a major failure of one of the evaporimeters with basket willow it was totally excluded from the study.

Table 7

Parameters of model WSMT with measured evaporation from open water in mm – 2011

Evap. No.		1	2	3	4	5
W	α	0.7364	0.6226		0.3842	0.6139
	β	-0.9849	-0.6471		-0.3159	-1.0012
	γ	0.7575	0.6938		0.6696	1.1290
	θ	-0.3006	-0.1062		-0.0759	-0.0680
	δ	24.7395	74.2855		79.3119	80.3004
Ś	α	0.5773	0.7051	0.5821	0.5245	0.4280
	β	-0.9764	-0.9901	-0.7958	-0.7171	-0.4230
	γ	0.7164	0.6326	0.7314	0.6480	0.8464
	θ	-0.3132	-0.6679	-0.7689	-0.6851	0.0787
	δ	19.2812	41.9607	47.7126	46.5605	113.9142
M	α	0.4553	0.2932	0.3873	0.3277	0.4198
	β	-0.0836	0.3262	0.2719	0.0733	-0.0195
	γ	0.7406	0.5024	0.5764	0.5325	0.7365
	θ	-0.0714	-0.2034	-0.1425	-0.4934	-0.0617
	δ	64.2986	62.2450	65.7966	58.7893	69.1694

Table 7. cont.

Evap. No.		1	2	3	4	5
T	α	0.2435	0.1296	0.2770	0.5783	0.4595
	β	0.0085	0.4337	0.0546	-0.6939	-0.4388
	γ	0.3184	0.4295	0.6455	0.6680	0.9391
	θ	0.9410	0.3244	0.3227	0.3746	0.0532
	δ	124.5560	126.9780	129.8161	130.0302	114.3774

Table 8

Parameters of model WSMT with measured evaporation from open water in mm – 2012

Evap. No.		1	2	3	4	5
W	α	1.0001	0.6440		0.4876	0.6737
	β	-1.8093	-0.4036		-0.4571	-0.9296
	γ	0.5903	0.3199		0.2504	0.4211
	θ	-0.7263	-1.3758		-49.9986	-0.8803
	δ	43.5154	42.0645		54.4926	45.3464
Ś	α	0.9598	0.8529	0.5325	0.6972	0.7044
	β	-2.0515	-1.7198	-0.7325	-1.4298	-1.3006
	γ	0.9440	1.0053	0.5656	0.9887	0.7374
	θ	-0.1719	-0.1035	-0.0768	-0.0970	-0.1533
	δ	79.5519	82.2694	87.1506	85.7991	73.1361
M	α	0.3517	0.3824	0.4704	0.3984	0.2521
	β	0.0077	-0.0299	-0.3881	-0.0830	0.1854
	γ	0.4467	0.4328	0.6856	0.4898	0.4996
	θ	-0.1097	-0.0776	-0.1142	-0.1119	-0.0737
	δ	81.7254	80.8261	80.1053	71.6370	68.1547
T	α	0.1160	0.3490	0.3607	0.7974	0.7969
	β	0.3203	-0.1896	-0.0991	-1.3208	-1.0581
	γ	0.3131	0.3550	0.3979	0.7585	0.6535
	θ	-26.2385	-1.4206	-1.8437	-0.0982	-0.0750
	δ	57.9753	63.4995	59.9591	72.5295	97.1335

Legend for Tables 7 and 8:

W – basket willow (*Salix viminalis*), Ś – Virginia mallow (*Sida hermafrodita* Rusby),
M – giant miscanthus grass (*Miscanthus x giganteus*), T – Jerusalem artichoke (*Helianthus tuberosus*),
α, β, γ, θ, δ – model parameters

Table 9

Parameters of model WSMT with measured evaporation from open water in mm – 2013

Evap. No.		1	2	3	4	5
W	α	1.2171	0.4336		0.0000	0.1738
	β	-1.5171	0.0410		1.0816	0.6024
	γ	0.3296	0.2826		0.2114	0.2062
	θ	-0.2772	3.0661		-1.2640	-2.2043
	δ	36.2752	190.4834		34.4920	34.5633
Ś	α	1.2580	1.3005	1.1121	1.2118	1.1785
	β	-1.5581	-1.6751	-1.2047	-1.5544	-1.4839
	γ	0.2649	0.2582	0.2761	0.2665	0.2820
	θ	-0.8807	-1.0069	1.2089	-1.5041	-0.8091
	δ	32.5683	32.8717	122.9662	35.2114	31.3649
M	α	0.5462	0.6491	0.1188	0.7970	0.7094
	β	0.3364	-0.1087	1.1147	-0.1804	-0.0914
	γ	0.1419	0.2066	0.2318	0.2367	0.2045
	θ	49.9998	25.6253	1.1242	-1.1148	-1.6067
	δ	154.4949	189.9703	187.4914	57.2931	52.5788
T	α	0.0491	0.2556	0.0000	0.2773	0.9408
	β	0.7252	0.3023	1.0090	1.5164	-0.5227
	γ	0.1701	0.1810	0.2873	-2.6956	0.1410
	θ	-2.7761	0.4818	0.6077	-1.2004	10.9389
	δ	55.6243	162.0695	76.1488	190.7129	148.0471

Table 10

Parameters of model WSMT with calculated reference evapotranspiration in mm – 2011

Evap. No.		1	2	3	4	5
W	α	0.8571	0.5808		0.4240	0.7142
	β	-0.6088	-0.1222		-0.1829	-0.8742
	γ	0.5918	0.6353		0.6819	1.1598
	θ	-0.8242	-0.1112		-0.0766	-0.0738
	δ	34.6768	78.2723		85.8718	87.9590
Ś	α	0.7297	0.7339	0.6304	0.5642	0.4126
	β	-0.6762	-0.5401	-0.4898	-0.4300	-0.0012
	γ	0.5449	0.5224	0.6381	0.5638	0.7417
	θ	-0.7230	-0.9816	-0.8851	-0.8574	0.1052
	δ	45.6239	42.7399	48.3785	47.2057	109.8172
M	α	0.3690	0.2371	0.3013	0.3130	0.3905
	β	0.4435	0.6684	0.6024	0.3381	0.3117
	γ	0.7016	0.4709	0.7644	0.4906	0.7598
	θ	-0.0663	-0.1884	-0.0499	-0.3963	-0.0525
	δ	66.1393	62.7402	77.3123	59.4473	76.0229

Table 10. cont.

Evap. No.		1	2	3	4	5
T	α	0.2772	0.1482	0.6006	0.8516	0.8601
	β	0.1297	0.5056	-0.5367	-1.0066	-1.0701
	γ	0.2610	0.3970	0.5296	0.5412	0.5985
	θ	1.1584	0.3537	-0.6545	-0.8518	-1.1597
	δ	123.5746	125.3993	45.4040	43.1300	42.6265

Legend for Tables 9 and 10:

W – basket willow (*Salix viminalis*), Ś – Virginia mallow (*Sida hermafrodita* Rusby),
M – giant miscanthus grass (*Miscanthus x giganteus*), T – Jerusalem artichoke (*Helianthus tuberosus*),
α, β, γ, θ, δ – model parameters

Table 11

Parameters of model WSMT with calculated reference evapotranspiration in mm – 2012

Evap. No.		1	2	3	4	5
W	α	1.0957	0.7214		0.4462	0.7241
	β	-0.9909	-0.3653		-0.1762	-0.2831
	γ	-0.5996	0.2209		0.1290	-0.4218
	θ	0.3961	-0.2938		-49.9977	0.5702
	δ	41.8377	108.0883		54.4967	44.5052
Ś	α	0.8979	0.8134	0.5385	0.6668	0.6845
	β	-1.5733	-1.3199	-0.5159	-1.1133	-1.0069
	γ	0.6995	0.7782	0.3923	0.8056	0.5479
	θ	-0.2335	-0.1283	-0.3776	-0.1153	-0.1808
	δ	83.3540	87.5360	98.1032	90.5551	76.2628
M	α	0.3444	0.3765	0.4456	0.3721	0.2354
	β	0.1490	0.1288	-0.1584	0.1344	0.3344
	γ	0.3497	0.3264	0.5581	0.3795	0.4244
	θ	-0.1396	-0.0980	-0.1332	-0.1295	-0.0779
	δ	86.3180	88.9825	83.3206	74.5999	70.4133
T	α	0.1543	0.4352	0.3755	0.7664	0.7403
	β	0.2605	-0.2667	-0.0151	-0.9455	-0.6701
	γ	0.2716	0.2979	0.2975	0.5376	0.4704
	θ	-1.7068	-0.8137	-2.7451	-0.1138	-0.1085
	δ	59.1229	92.9936	60.2654	77.9720	109.7763

Table 12

Parameters of model WSMT with calculated reference evapotranspiration in mm – 2013

Evap. No.		1	2	3	4	5
W	α	1.0354	0.3619		0.0000	0.1701
	β	-1.0915	0.2184		1.2738	0.6024
	γ	0.2500	0.2494		0.1457	0.1905
	θ	-0.1799	26.6183		42.0744	-2.5654
	δ	46.8778	189.9953		189.6246	34.6723

Table 12. cont.

Evap. No.		1	2	3	4	5
Ś	α	1.0599	1.1154	0.9193	1.0508	1.0062
	β	-1.1019	-1.2576	-0.8136	-1.2066	-1.0837
	γ	0.1746	0.1624	0.2027	0.1989	0.1935
	θ	-1.4610	-2.1778	2.2470	-0.9300	-1.2124
	δ	34.2020	34.3641	120.8168	55.6653	32.8954
M	α	0.5682	0.5713	0.1585	0.6805	0.6148
	β	0.2652	0.1355	1.0102	0.0159	0.0694
	γ	0.0742	0.1692	0.2136	0.2023	0.1696
	θ	-3.4693	-1.1848	19.4439	-0.9539	-0.8954
	δ	58.8033	55.7302	189.0252	59.2691	55.9214
T	α	0.0856	0.2528	0.0000	0.3348	0.9432
	β	0.6211	0.3060	1.0090	1.2287	-0.6629
	γ	0.1621	0.1484	0.2873	-2.1458	0.1399
	θ	-26.6200	0.5576	0.6077	-1.5945	-0.8991
	δ	55.9900	163.4624	76.1488	190.8901	97.0137

Legend for Tables 11 and 12:
W – basket willow (*Salix viminalis*), Ś – Virginia mallow (*Sida hermafrodita* Rusby),
M – giant miscanthus grass (*Miscanthus x giganteus*), T – Jerusalem artichoke (*Helianthus tuberosus*),
α, β, γ, θ, δ – model parameters

The calculations permitted to obtain, apart from the values of the parameters, information on the degree of fit of the model to the empirical values through the determination of the basic measures of fit, i.e. the coefficients of correlation, coefficients of determination and the relative deviation errors. As far as the variation of the parameters obtained is concerned, the first of them, α, is closely related with the input data, i.e. the diurnal sums of evaporation from open water surface measured by means of evaporimeters EWP 992 or, alternatively, calculated according to the formula proposed by Penman–Monteith, the actual calculations being made with the EVAPO application. Parameter β is a correction parameter, while the remaining three parameters, γ, θ and δ are related with the diurnal sum of atmospheric precipitation. The fact of making the calculations separately for each evaporimeter and for each energy crop permitted the observation of variations for the particular energy crop species. The analysis of variation of the model parameters obtained – in the consecutive years of the field experiment, for the particular evaporimeters within individual energy crop species, and the variation between them, indicated a high sensitivity of the model developed. The soil monoliths were taken for each evaporimeter at the same site, so theoretically the monoliths should be identical in every pot. However, the estimation of their mass made at the start of the study revealed their diversity which consisted in differences in the sampled mass of the soil monoliths. The differentiation in the soil mass in the evaporimeters was reflected in differences in their water content. For this reason the energy crop plants in the pots of the evaporimeters had varied possibilities of making use of soil water resources in the course of their vegetation. Graphic images of the fitting of the WSTM model to empirical data, obtained in the process of calculations, values of coefficients of determination and relative errors of deviation are presented, as examples, in Figures 18, 20, 22 and 24. Those were preceded with graphic representations of the input data in the form of variation of diurnal sums of measured evapotranspiration in the particular evaporimeters with the four energy crop plant species under study, and the measured values of diurnal sums of evaporation from open water surface, determined by means of evaporimeter EWP 992. The second variant included also the values of diurnal sums of measured evapotranspiration in the particular evaporimeters, while the measured values of evaporation from open water surface were replaced with the reference evapotranspiration (ET_0) computed with the use of the EVAPO application according to the “FAO–Penman–Monteith” formula. As an example, this monograph presents the results of calculations performed with the developed model for the year 2013. The input data for the individual pots were denoted with number 1, with the exception of Jerusalem artichoke for which evaporimeter No. 5 was the representative. The pots with plants representing all four studied plant species are presented in Figures 17 and 19 – variant one, and in Figures 21 and 23 – variant two. Whereas, the graphic results of fitting after the calculations with the model are presented in Figures 18 and 20, and Figures 22 and 24, respectively. Comparative analysis of the two groups of data, i.e. the input data and the results, indicates a high degree of fit of the values determined with the model to the data on the actual evapotranspiration measured in the evaporimeters, in spite of the notable variation of the values of coefficients of determination and relative errors of deviation obtained as a result of the calculations.

The next stage of the analyses was the performance of calculations, using the model developed, based on averaged diurnal values of evapotranspiration for the particular plant species within each year separately. Just like in the former case, two variants of input data were analysed. The first with the use of evaporation from open water surface, and the second with data calculated with the EVAPO application. The values of the model parameters obtained from the calculations are presented in Table 13. Graphic presentations of the input data and their fitting with the WSMT model to the empirical data for the years 2011–2013 for giant miscanthus grass and for both variants of input data applied are presented in Figures 25 and 27 (variant 1) and 26 and 28 (variant 2). Comparative analysis of the input data for that stage of the study with the results obtained revealed a notable improvement in the quality of values calculated with the model. Also the calculated coefficients of determination became more uniform, and the errors of fit had now considerably lower values compared to the calculations from the preceding stage.

Due to the fact that out of the whole three-year period of the study the accumulated source materials for the years 2012 and 2013 were the most complete, it was decided to average the data for those two years as input data for the WSMT model, perform the calculation of the model parameters (Tab. 14) and acquire the most important information on the relative errors of deviation. That procedure was performed for each of the plant species individually and, as in the previous two stages, for both variants of input data. To create a possibility of comparing the input data for both the variants as well as the results obtained, the variation of the input data and their fitting after the application of the WSMT model are presented here in a graphic form. The input data are presented in Figures 29, 31, 33, 35, 37, 39, 41 and 43, while the runs of the calculated values in Figures 30, 32, 34, 36, 38, 40, 42 and 44.

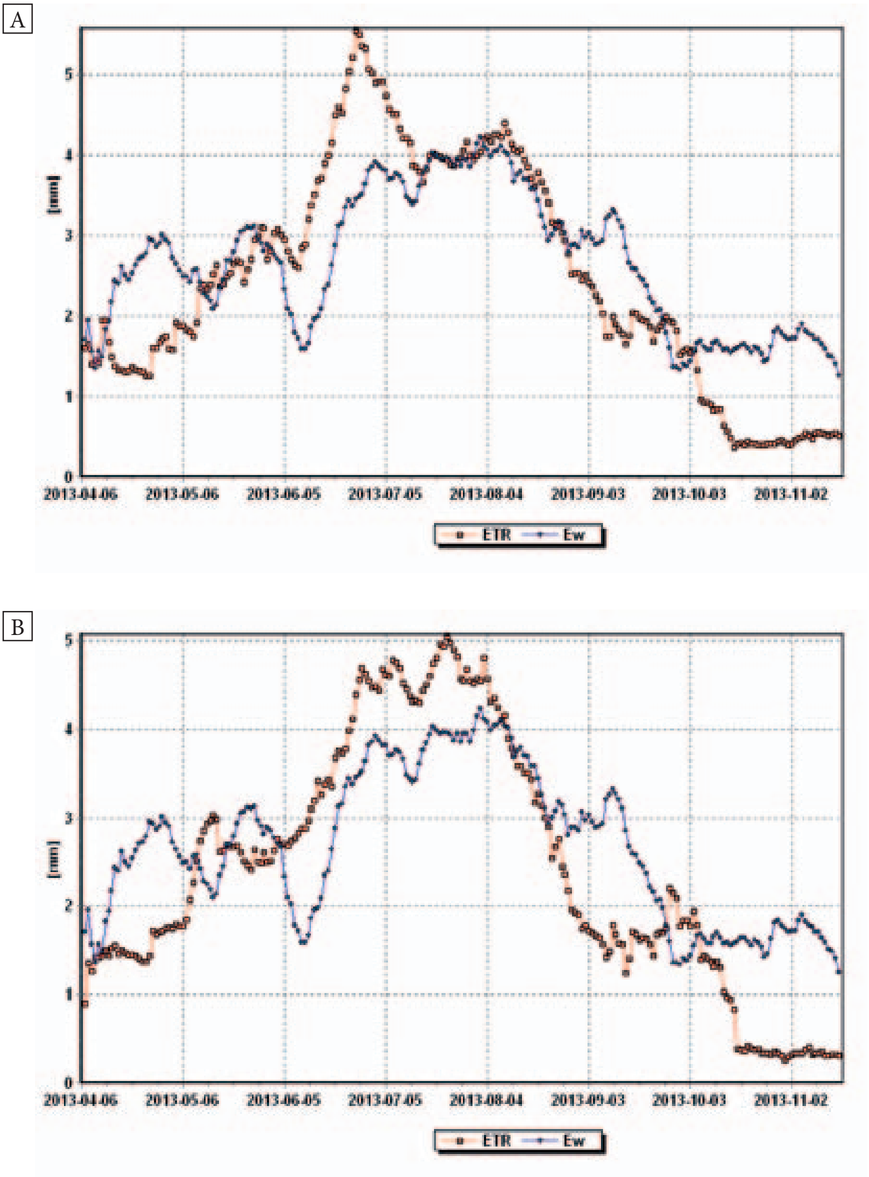


Fig. 17. Empirical input data from 2013, evaporimeter No. 1:
ETR – evapotranspiration, Ew – input data measured with EWP 992,
A – Basket willow (*Salix viminalis*), B – Virginia mallow (*Sida hermafrodita* Rusby)
Source: own elaboration

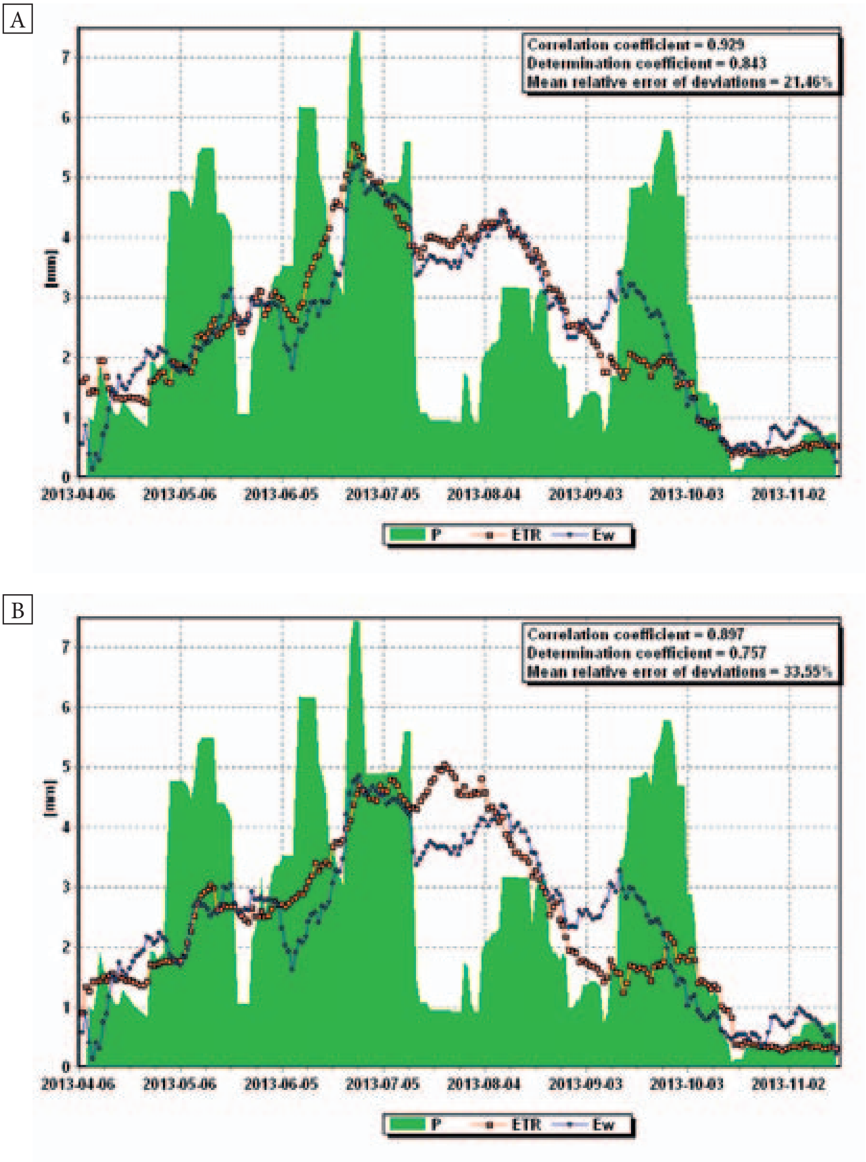
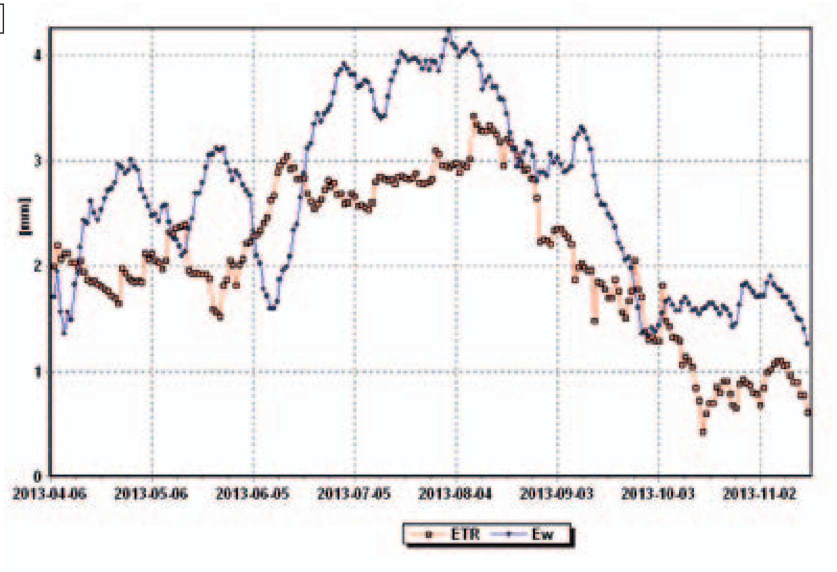


Fig. 18. Fitting of WSMT model (ETR – evapotranspiration) to empirical data (P – precipitation, Ew – input data measured with EWP 992) from 2013, evaporimeter No. 1: A – Basket willow (*Salix viminalis*), B – Virginia mallow (*Sida hermafrodita* Rusby)
Source: own elaboration

A



B

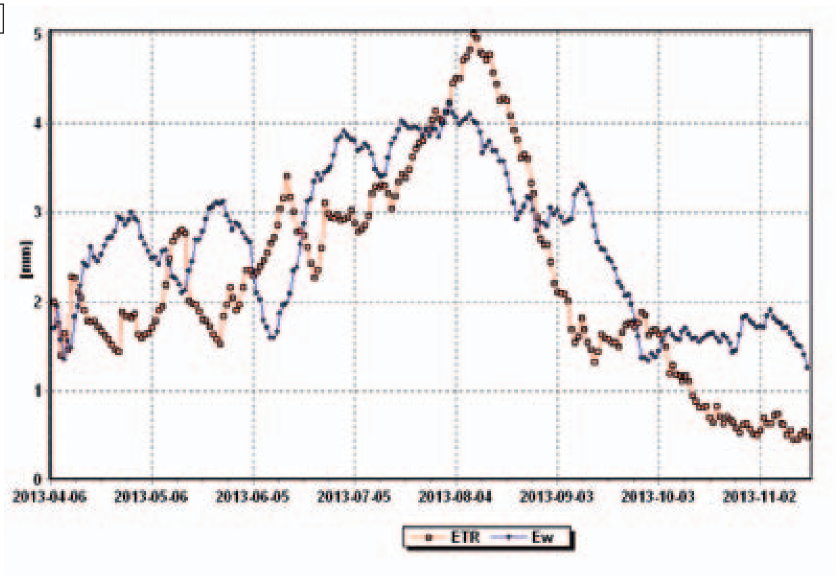


Fig. 19. Empirical input data from 2013, evaporimeters No. 1 and 5:
ETR – evapotranspiration, Ew – input data measured with EWP 992
A – Giant miscanthus grass (*Miscanthus x giganteus*)
B – Jerusalem artichoke (*Helianthus tuberosus*)
Source: own elaboration

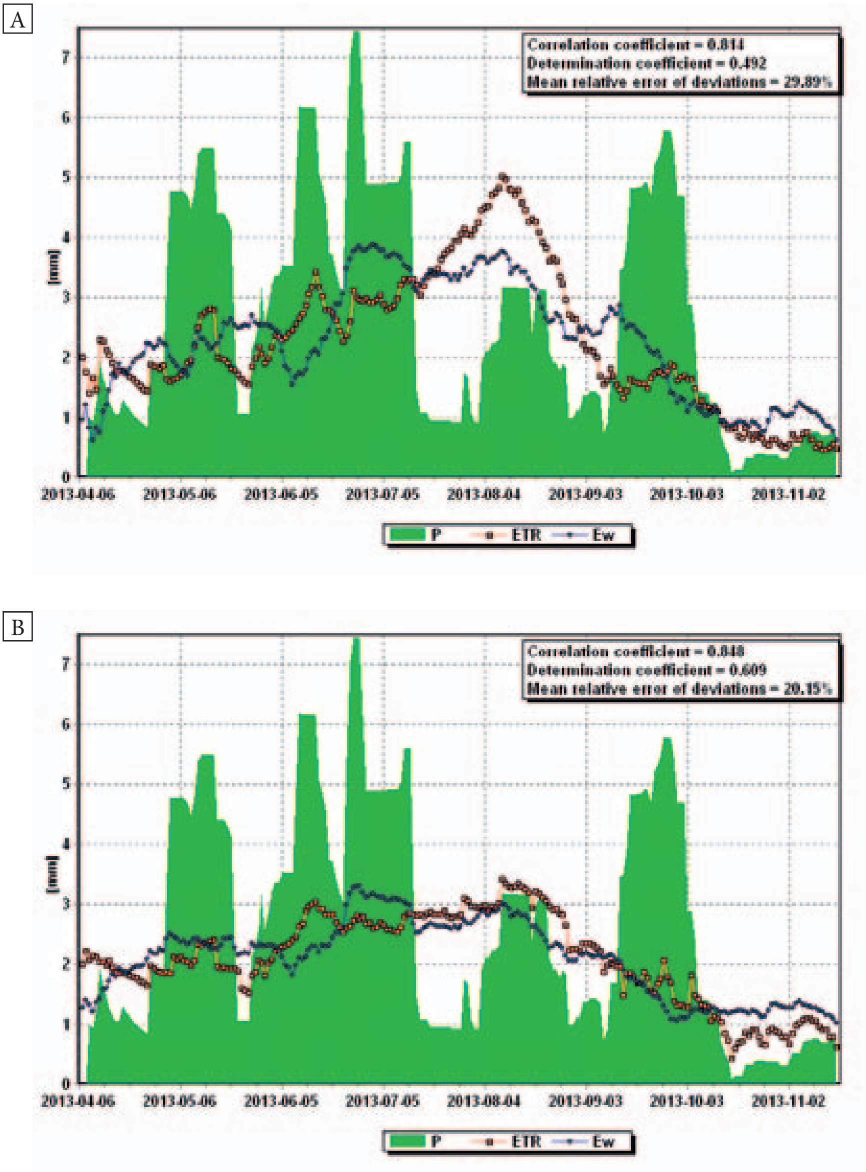


Fig. 20. Fitting of WSMT model (ETR – evapotranspiration) to empirical data (P – precipitation, Ew – input data measured with EWP 992) from 2013, evaporimeters No. 1 and 5:
A – Giant miscanthus grass (*Miscanthus x giganteus*)
B – Jerusalem artichoke (*Helianthus tuberosus*)
Source: own elaboration

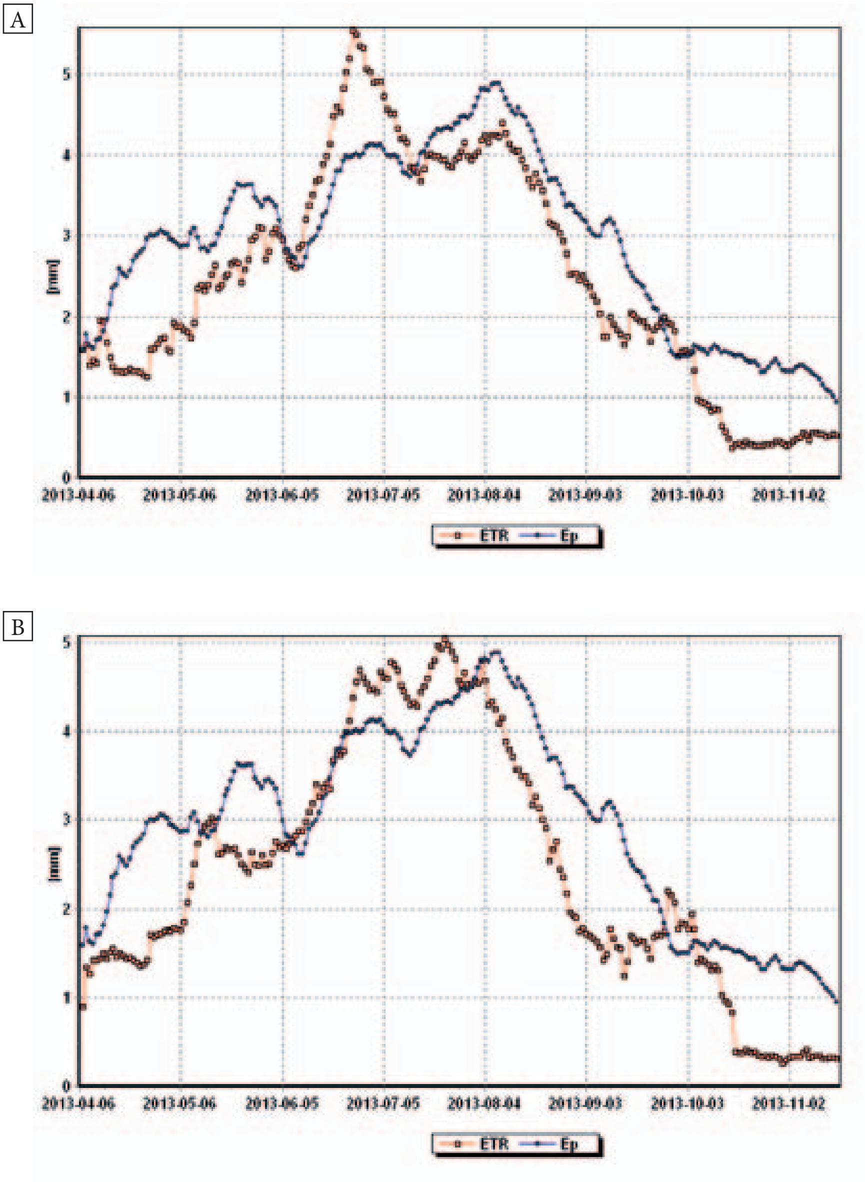


Fig. 21. Empirical input data from 2013, evaporimeter No. 1:
ETR – evapotranspiration, Ep – input data calculated with EVAPO
A – Basket willow (*Salix viminalis*), B – Virginia mallow (*Sida hermafrodita* Rusby)
Source: own elaboration

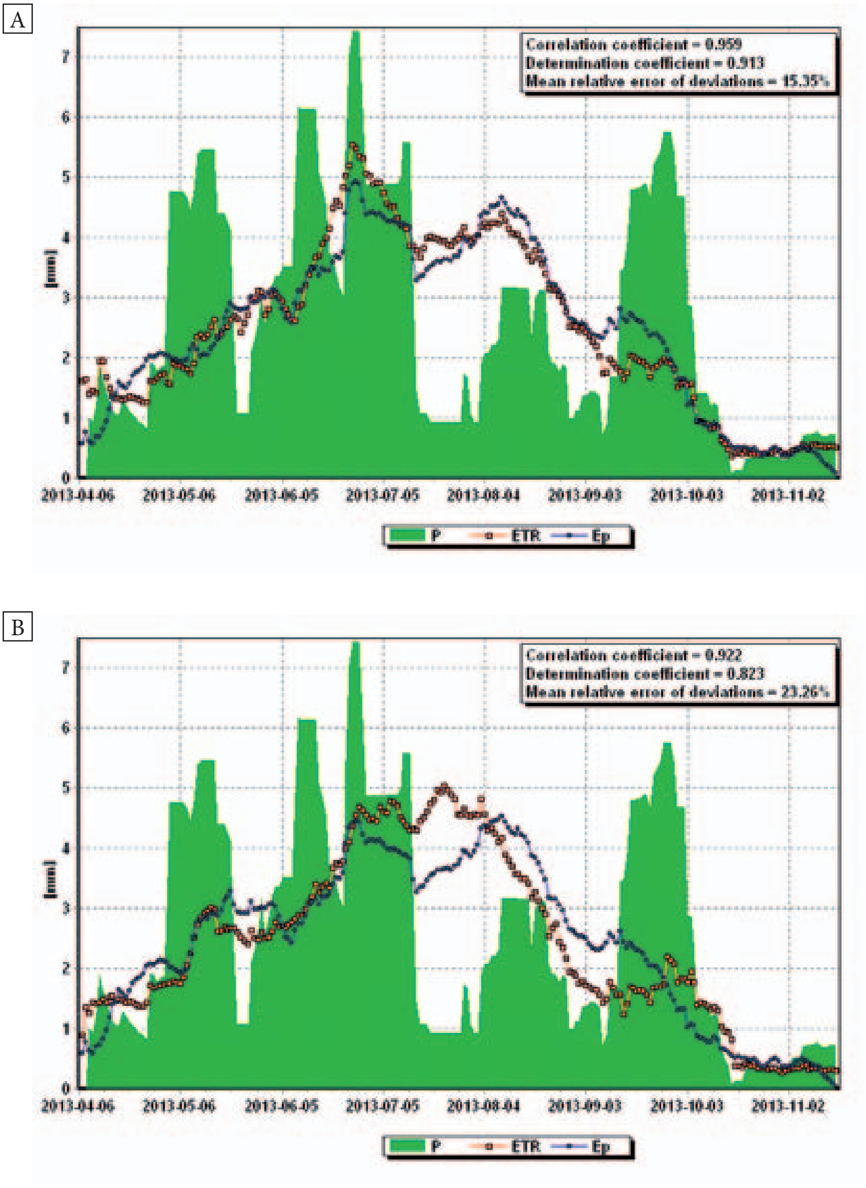


Fig. 22. Fitting of WSMT model (ETR – evapotranspiration) to empirical data (P – precipitation, Ep – input data calculated with EVAPO) from 2013, evaporimeter No. 1:
A – Basket willow (*Salix viminalis*), B – Virginia mallow (*Sida hermafrodyta* Rusby)
Source: own elaboration

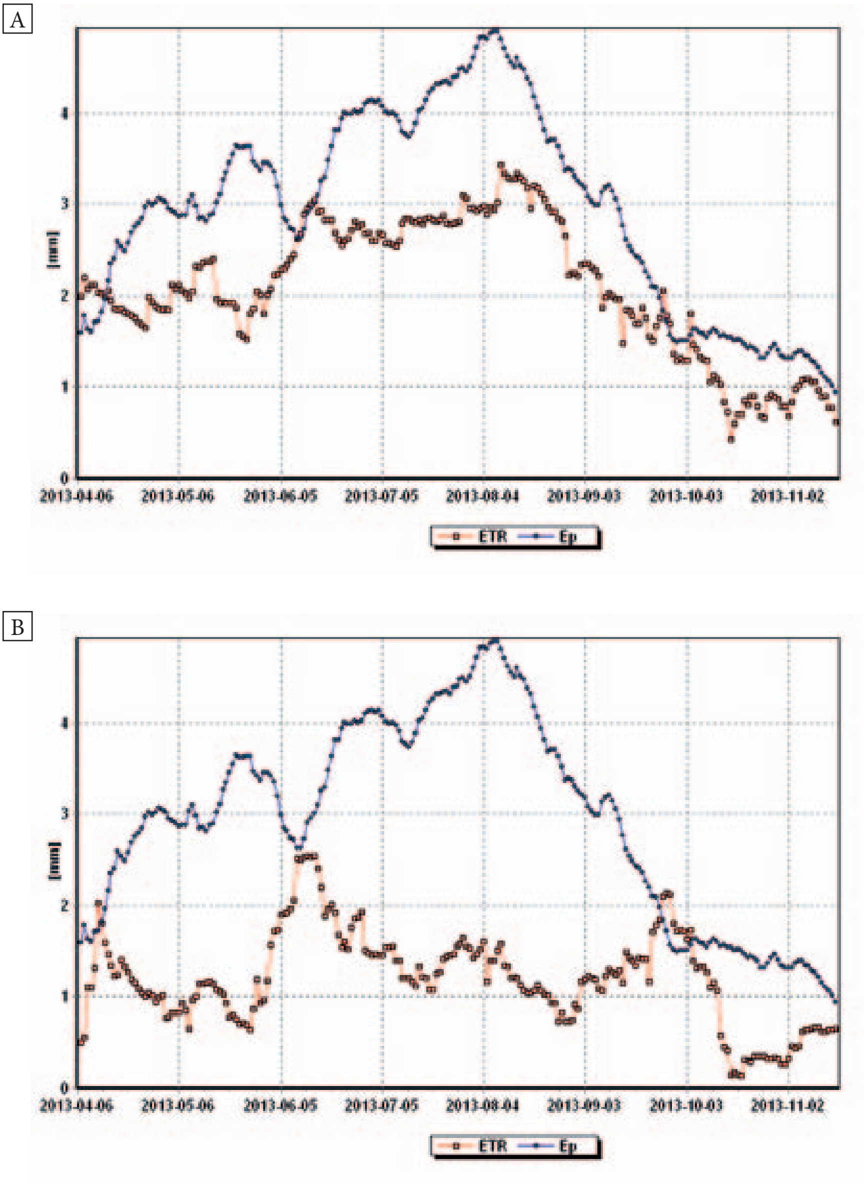


Fig. 23. Empirical input data from 2013, evaporimeter No. 1:
ETR – evapotranspiration, Ep – input data calculated with EVAPO
A – Giant miscanthus grass (*Miscanthus x giganteus*)
B – Jerusalem artichoke (*Helianthus tuberosus*)
Source: own elaboration

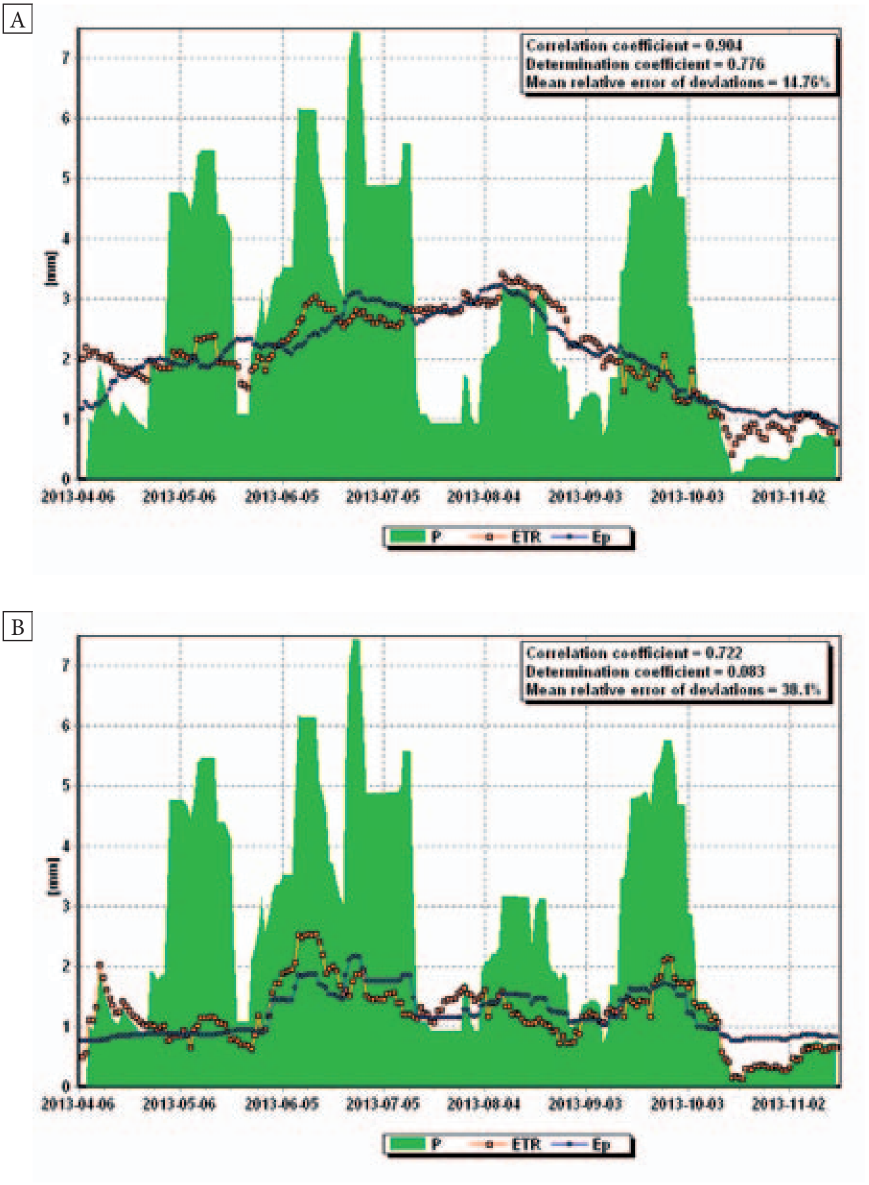


Fig. 24. Fitting of WSMT model (ETR – evapotranspiration) to empirical data (P – precipitation, Ep – input data calculated with EVAPO) from 2013, evaporimeter No. 1:
A – Giant micanthus grass (*Miscanthus x giganteus*)
B – Jerusalem artichoke (*Helianthus tuberosus*)
Source: own elaboration

Table 13

Values of WSMT model parameters calculated for averaged values of field evaporation from particular groups of evaporimeters and from EWP 992 and calculated with EVAPO for the years 2011–2013

Year		2011		2012		2013	
Evap. Mo.		mean EVAPO	mean EWP 992	mean EVAPO	mean EWP 992	mean EVAPO	mean EWP 992
W	α	0.6991	0.4940	0.7183	0.7592	0.4208	0.4742
	β	-0.5678	-0.2666	-0.6289	-1.0426	0.1721	0.0546
	γ	0.8120	0.7275	0.2403	0.4493	0.2583	0.2933
	θ	-0.0762	-0.0682	-1.0926	-0.7259	-0.2453	-0.3010
	δ	79.6867	62.5810	43.6959	42.8346	35.8636	34.1121
Ś	α	0.6968	0.6643	0.7122	0.7433	1.0450	1.2433
	β	-0.6422	-1.0511	-1.0509	-1.4064	-1.1641	-1.6240
	γ	0.5883	0.6926	0.6398	0.8471	0.1874	0.2764
	θ	-0.7868	-0.6357	-0.1150	-0.1002	-0.8551	-0.6019
	δ	44.7929	44.1741	77.8197	73.5827	34.8945	32.7003
M	α	0.3374	0.4102	0.3534	0.3687	0.5441	0.6150
	β	0.5034	0.0393	0.1122	-0.0700	0.2768	0.1686
	γ	0.5696	0.6140	0.4212	0.5269	0.2171	0.2484
	θ	-0.1098	-0.1173	-0.1025	-0.0929	-0.8897	-0.7974
	δ	62.6073	61.9749	73.8827	70.6374	56.8547	54.4647
T	α	0.6126	0.3354	0.5102	0.5067	0.3042	0.3675
	β	-0.5593	-0.0758	-0.4125	-0.5937	0.9956	0.2749
	γ	0.5152	0.6171	0.4419	0.5831	-1.5470	0.2006
	θ	-0.7652	0.2857	-0.0869	-0.0842	-1.5456	21.1631
	δ	44.3221	127.6475	75.8226	69.7416	189.8764	189.8744

Table 14

Values of WSMT model parameters calculated for averaged values of field evaporation from particular groups of evaporimeters and years 2012 and 2013 and from EWP 992, and calculated with EVAPO

		mean EVAPO – 2012 and 2013	mean EWP 992–2012 and 2013
W	α	0.6299	0.7833
	β	-0.2480	-0.6638
	γ	0.1663	0.2135
	θ	-0.3469	-0.4351
	δ	39.2023	38.9962
Ś	α	1.1514	1.2893
	β	-1.0643	-1.8231
	γ	-0.0307	0.2224
	θ	1.2328	-1.1527
	δ	64.9568	66.0139
M	α	0.5202	0.6615
	β	0.1911	-0.1733
	γ	0.1705	0.2031
	θ	-0.5511	-0.7106
	δ	67.0012	65.4134
T	α	0.5671	0.6939
	β	-0.0848	-0.4130
	γ	0.0911	0.1330
	θ	-1.3468	-1.5431
	δ	62.0572	61.7673

Legend for Tables 13 and 14:

W – Basket willow (*Salix viminalis*), Ś – Virginia mallow (*Sida hermafrodita* Rusby),
M – Giant miscanthus grass (*Miscanthus x giganteus*), T – Jerusalem artichoke (*Helianthus tuberosus*),
α, β, γ, θ, δ – model parameters

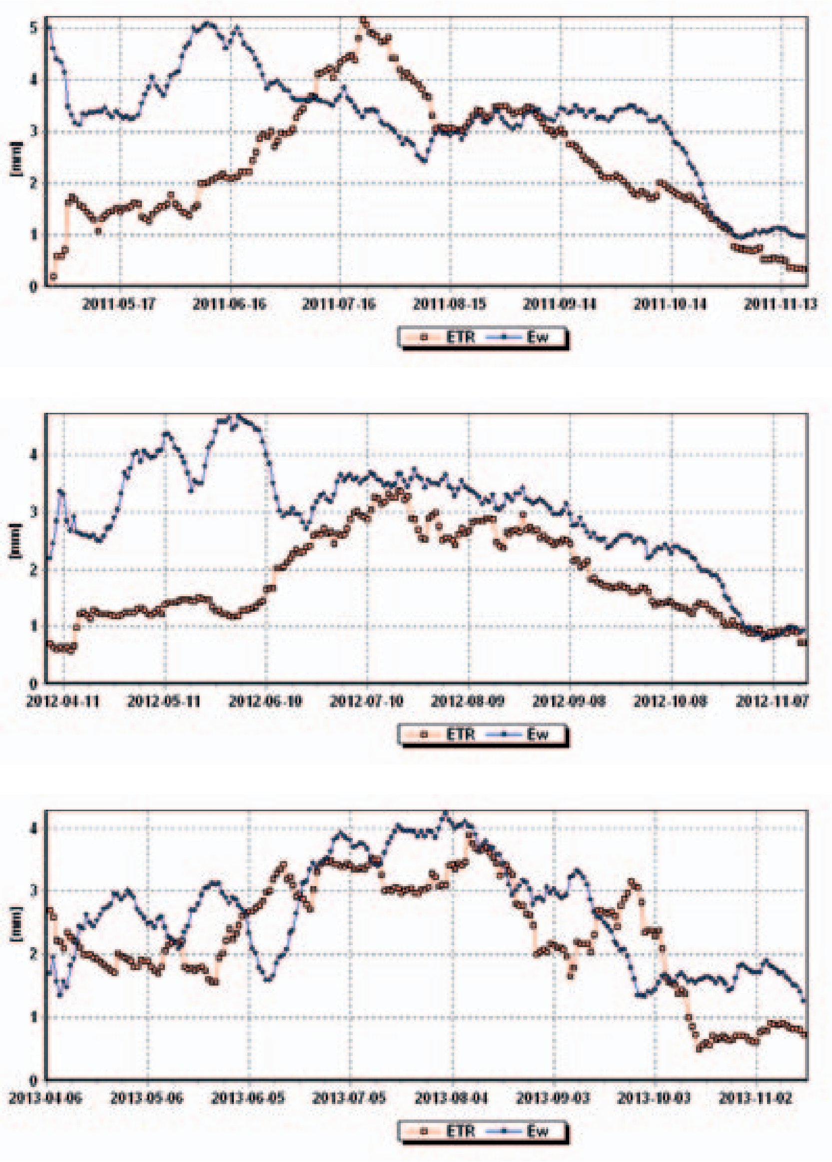


Fig. 25. Empirical input data in successive years, values averaged for plant species
ETR – evapotranspiration, Ew – input data measured with EWP 992
Giant miscanthus grass (*Miscanthus x giganteus*). Source: own elaboration

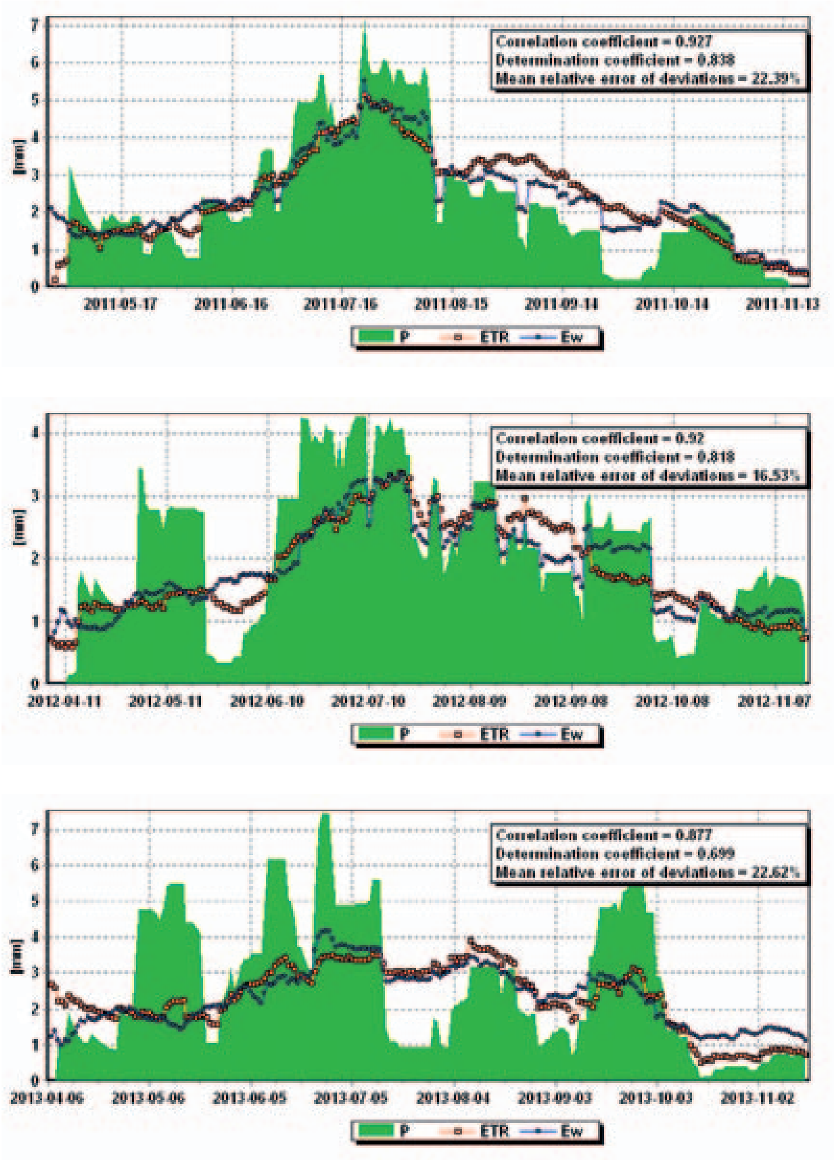


Fig. 26. Fitting of WSMT model (ETR – evapotranspiration) to empirical data (P – precipitation, Ew – input data measured with EWP 992) in successive years, values averaged for plant species Giant miscanthus grass (*Miscanthus x giganteus*). Source: own elaboration

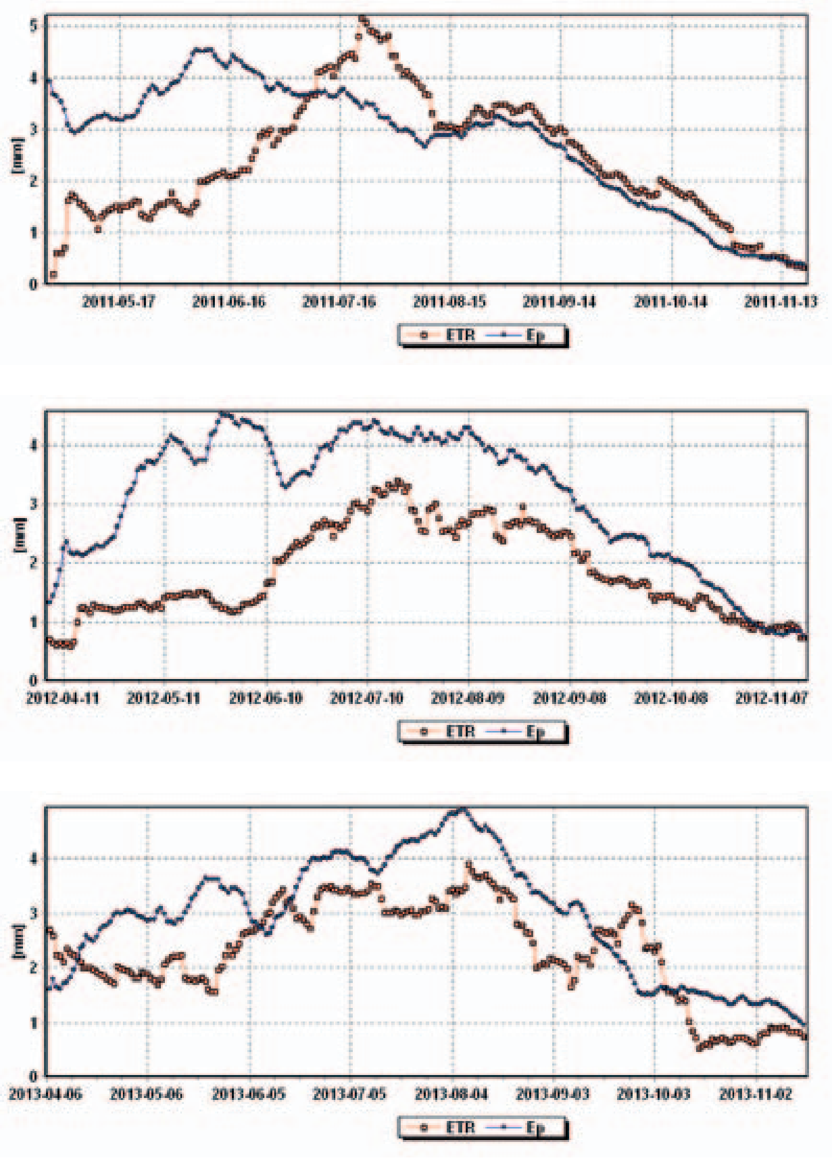


Fig. 27. Empirical input data in successive years, values averaged for plant species
ETR – evapotranspiration, Ep – input data calculated with EVAPO
Giant miscanthus grass (*Miscanthus x giganteus*). Source: own elaboration

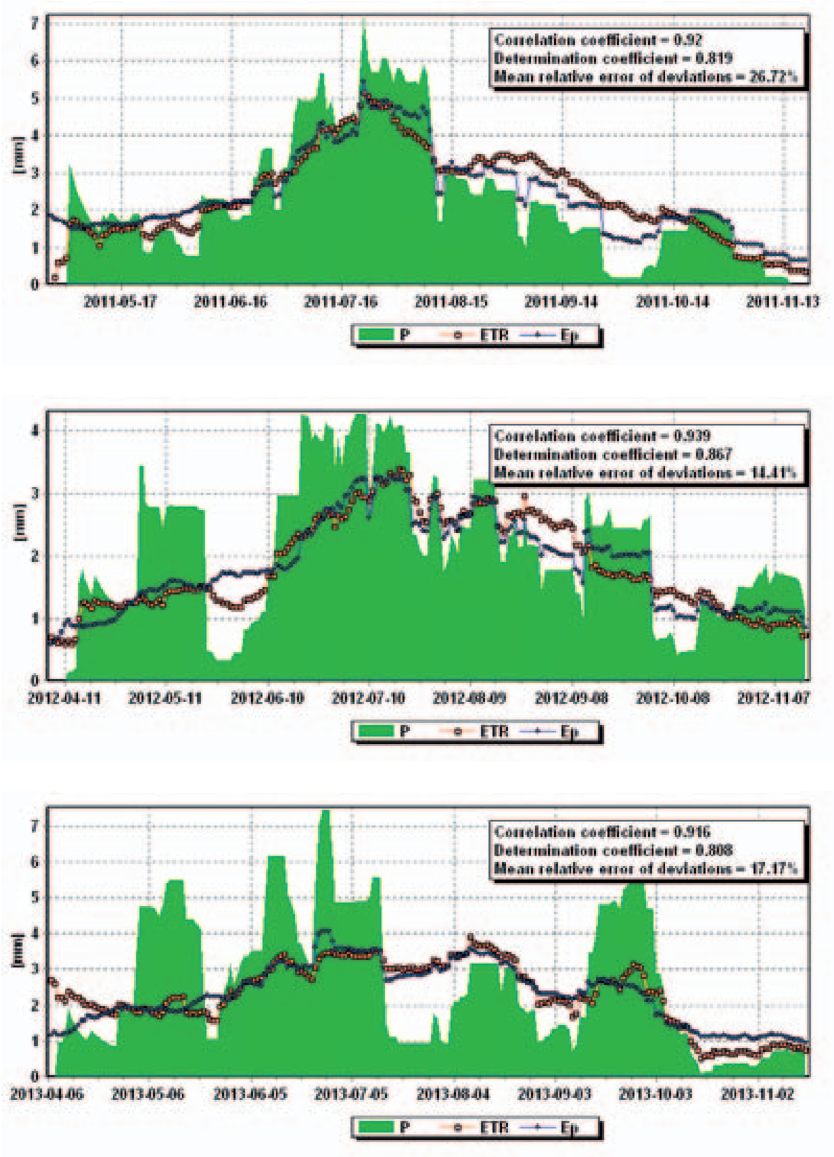


Fig. 28. Fitting of WSMT model (ETR – evapotranspiration) to empirical data (P – precipitation, Ep – input data calculated with EVAPO) in successive years, values averaged for plant species Giant miscanthus grass (*Miscanthus x giganteus*). Source: own elaboration

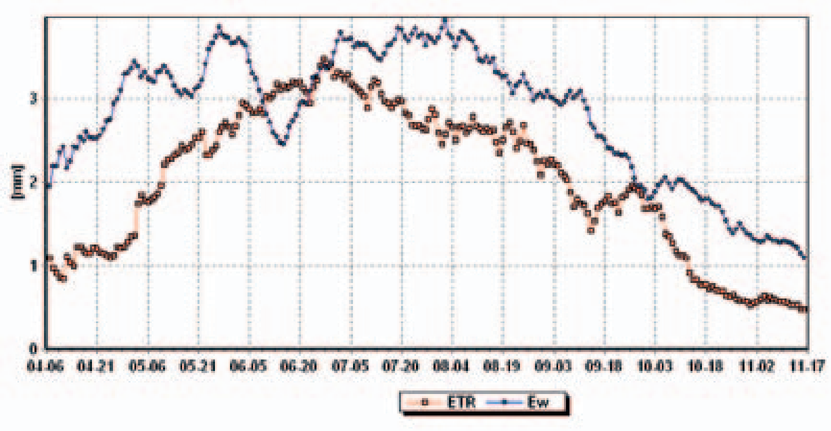


Fig. 29. Averaged empirical input data from 2012 and 2013
ETR – evapotranspiration, Ew – input data measured with EWP 992
Basket willow (*Salix viminalis*). Source: own elaboration

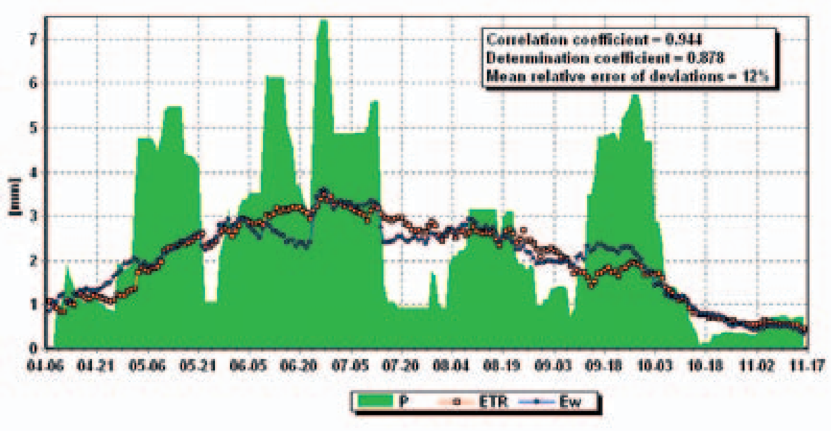


Fig. 30. Fitting of WSMT model (ETR – evapotranspiration) to averaged empirical data
(P – precipitation, Ew – input data measured with EWP 992) from 2012 and 2013
Basket willow (*Salix viminalis*). Source: own elaboration

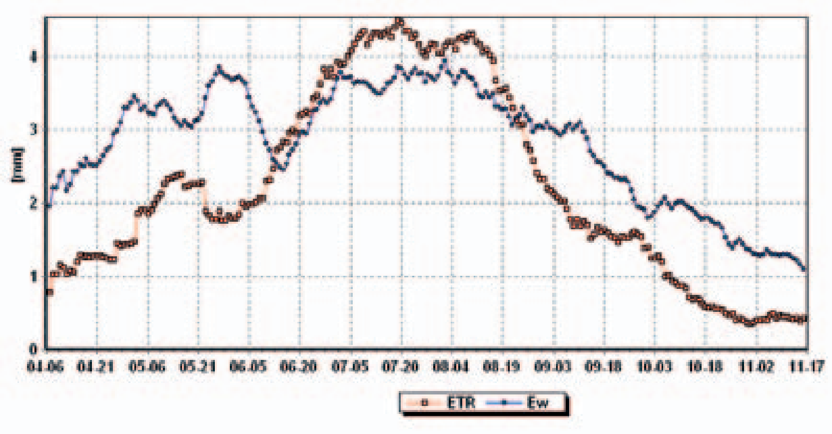


Fig. 31. Averaged empirical input data from 2012 and 2013
ETR – evapotranspiration, Ew – input data measured with EWP 992
Virginia mallow (*Sida hermafrodita* Rusby). Source: own elaboration

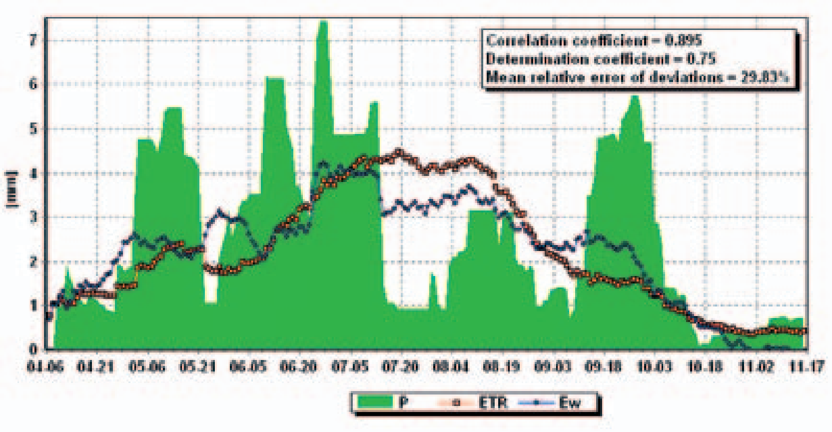


Fig. 32. Fitting of WSMT model (ETR – evapotranspiration) to averaged empirical data
(P – precipitation, Ew – input data measured with EWP 992) from 2012 and 2013
Virginia mallow (*Sida hermafrodita* Rusby). Source: own elaboration

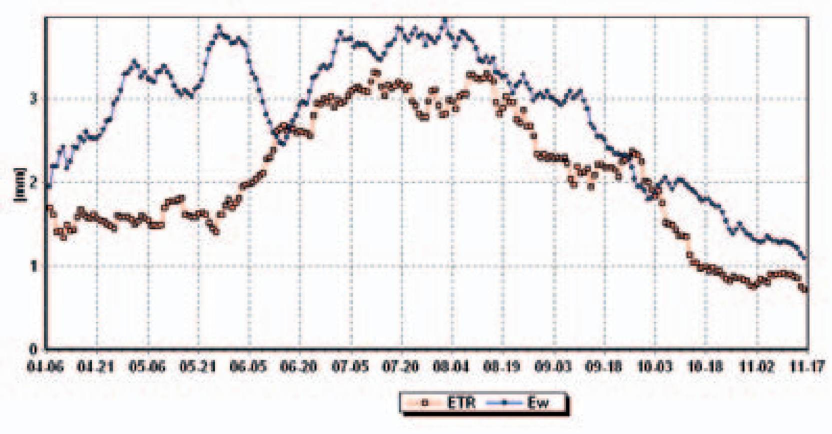


Fig. 33. Averaged empirical input data from 2012 and 2013
ETR – evapotranspiration, Ew – input data measured with EWP 992
Giant miscanthus grass (*Miscanthus x giganteus*). Source: own elaboration

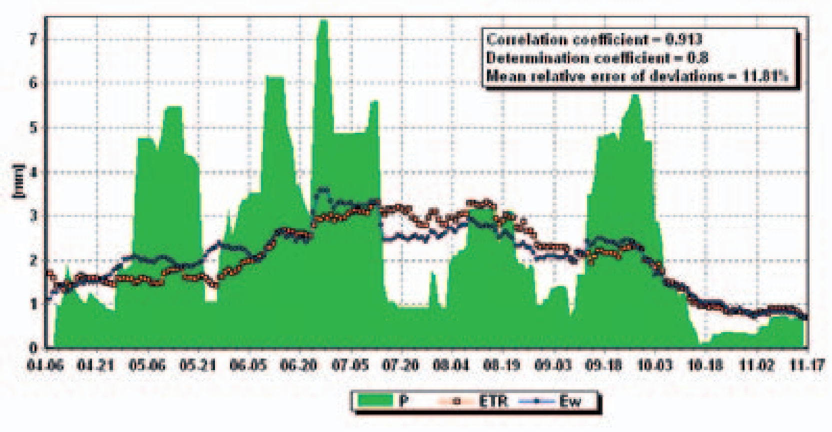


Fig. 34. Fitting of WSMT model (ETR – evapotranspiration) to averaged empirical data
(P – precipitation, Ew – input data measured with EWP 992) from 2012 and 2013
Giant miscanthus grass (*Miscanthus x giganteus*). Source: own elaboration

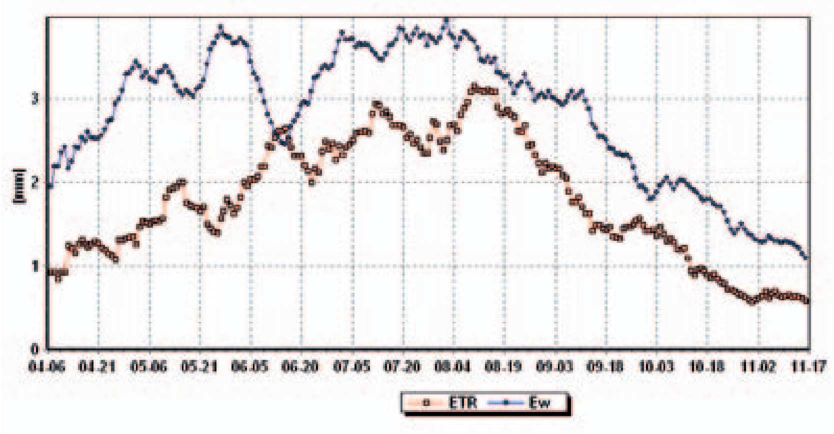


Fig. 35. Averaged empirical input data from 2012 and 2013
ETR – evapotranspiration, Ew – input data measured with EWP 992
Jerusalem artichoke (*Helianthus tuberosus*). Source: own elaboration

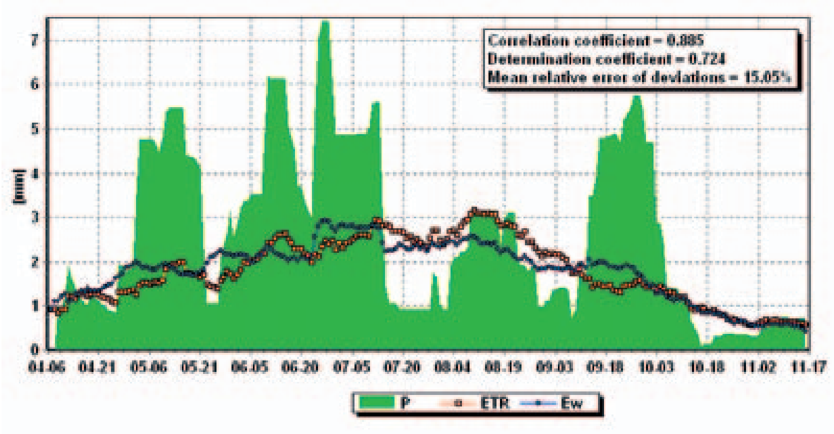


Fig. 36. Fitting of WSMT model (ETR – evapotranspiration) to averaged empirical data
(P – precipitation, Ew – input data measured with EWP 992) from 2012 and 2013
Jerusalem artichoke (*Helianthus tuberosus*). Source: own elaboration

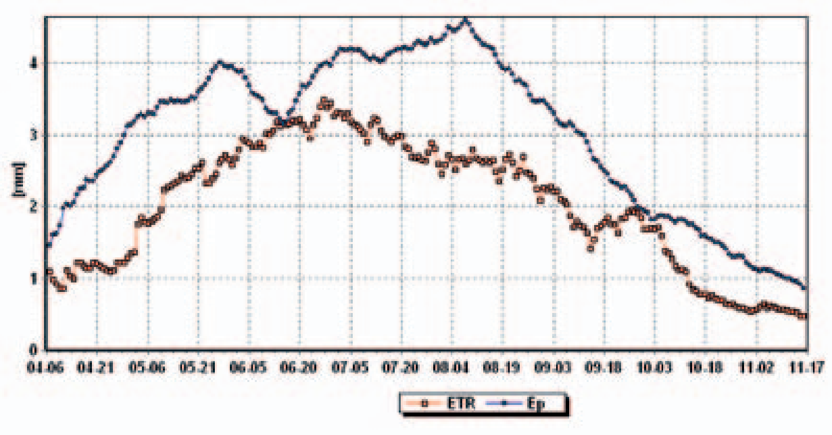


Fig. 37. Averaged empirical input data from 2012 and 2013
ETR – evapotranspiration, Ep – input data calculated with EVAPO
Basket willow (*Salix viminalis*). Source: own elaboration

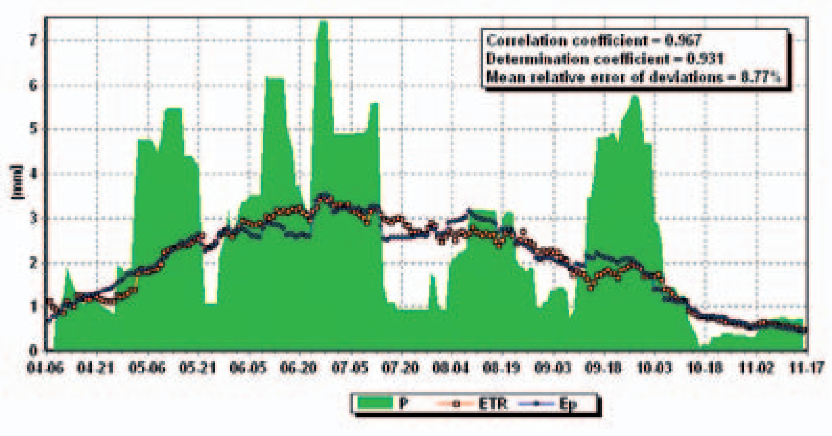


Fig. 38. Fitting of WSMT model (ETR – evapotranspiration) to averaged empirical data
(P – precipitation, Ep – input data calculated with EVAPO) from 2012 and 2013
Basket willow (*Salix viminalis*). Source: own elaboration

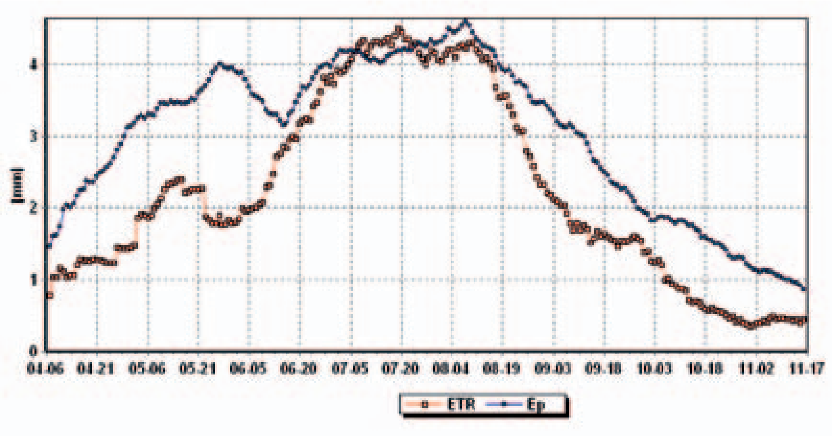


Fig. 39. Averaged empirical input data from 2012 and 2013
ETR – evapotranspiration, Ep – input data calculated with EVAPO
Virginia mallow (*Sida hermafrodita* Rusby). Source: own elaboration

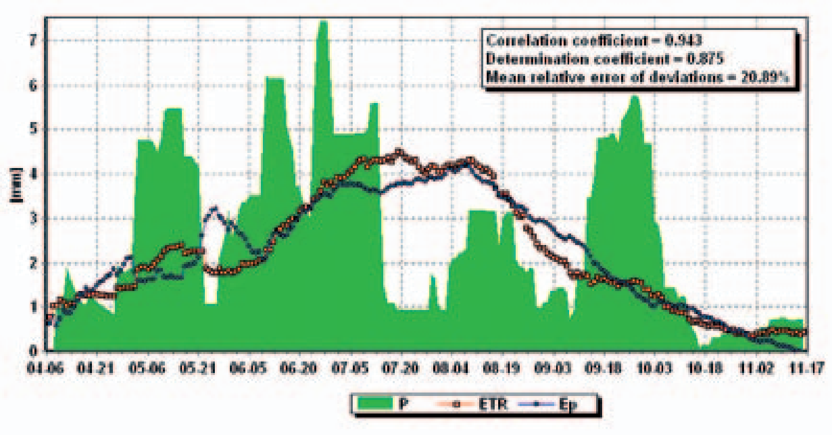


Fig. 40. Fitting of WSMT model (ETR – evapotranspiration) to averaged empirical data
(P – precipitation, Ep – input data calculated with EVAPO) from 2012 and 2013
Virginia mallow (*Sida hermafrodita* Rusby). Source: own elaboration

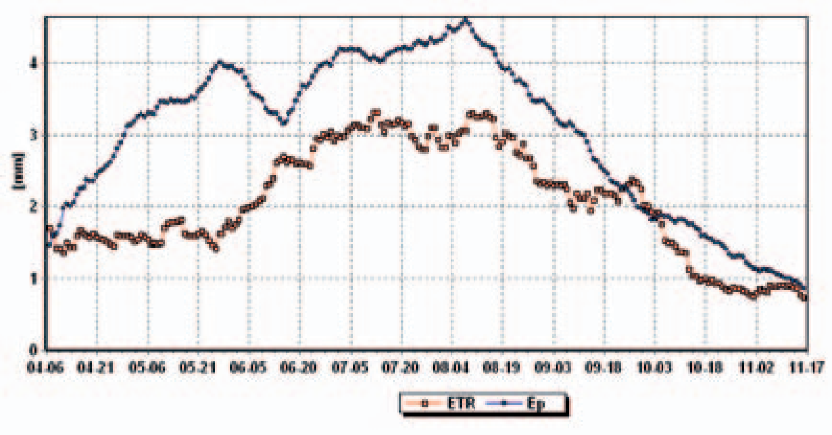


Fig. 41. Averaged empirical input data from 2012 and 2013
ETR – evapotranspiration, Ep – input data calculated with EVAPO
Giant miscanthus grass (*Miscanthus x giganteus*). Source: own elaboration

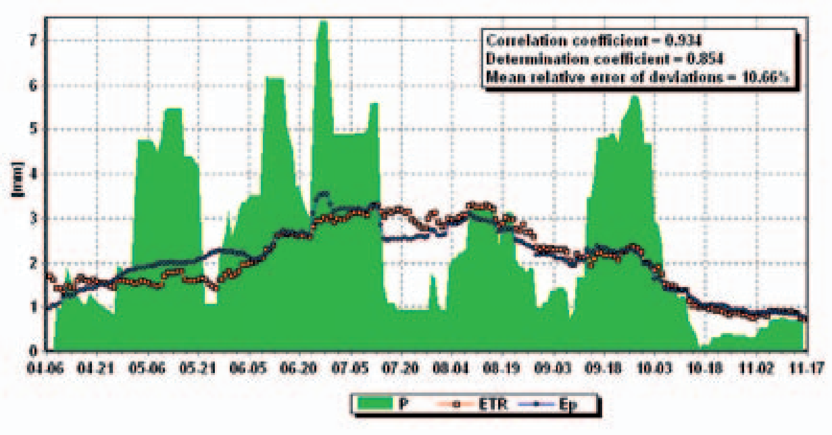


Fig. 42. Fitting of WSMT model (ETR – evapotranspiration) to averaged empirical data
(P – precipitation, Ep – input data calculated with EVAPO) from 2012 and 2013
Giant miscanthus grass (*Miscanthus x giganteus*). Source: own elaboration

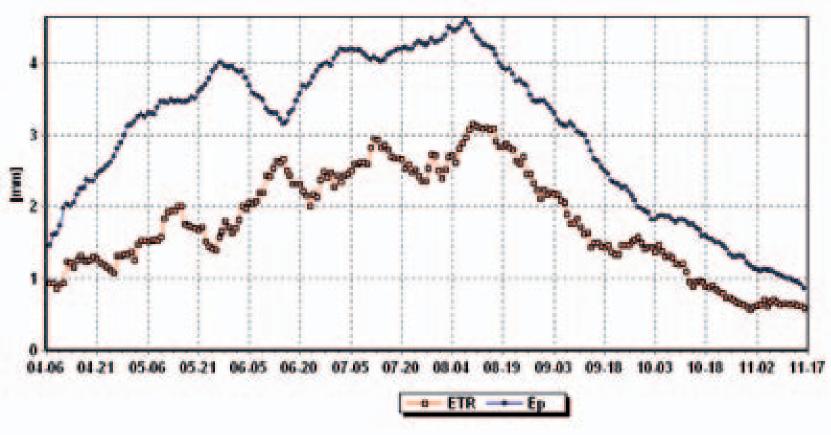


Fig. 43. Averaged empirical input data from 2012 and 2013
ETR – evapotranspiration, Ep – input data calculated with EVAPO
Jerusalem artichoke (*Helianthus tuberosus*). Source: own elaboration

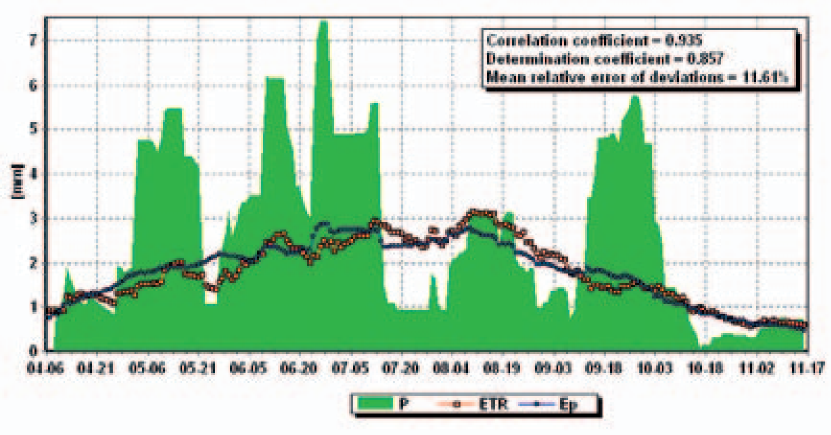


Fig. 44. Fitting of WSMT model (ETR – evapotranspiration) to averaged empirical data
(P – precipitation, Ep – input data calculated with EVAPO) from 2012 and 2013
Jerusalem artichoke (*Helianthus tuberosus*). Source: own elaboration

The collected observation material from the years 2011–2013 permitted the development and verification of the WSMT model on a large data set. The model created permits the calculation of actual evapotranspiration for 24-hour time intervals for four energy crop species, i.e. Basket willow (*Salix viminalis*), Virginia mallow (*Sida hermafrodita* Rusby), Giant Miscanthus grass (*Miscanthus x giganteus*) and Jerusalem artichoke (*Helianthus tuberosus*). The initial version of the model was created with the use of experimental data from only one measurement season. The input data used then were the diurnal sums of measured evapotranspiration of the energy crop plants and evaporation from open water surface, and diurnal sums of atmospheric precipitation. The calculations performed initially for two energy plant species (basket willow and Virginia mallow) and the results obtained with the use of the model confirmed the viability of the chosen direction of model construction [Żyromski et al. 2012a]. The preliminary verification of the model was conducted on the other two energy plant species, i.e. giant miscanthus grass and Jerusalem artichoke [Żyromski et al. 2012b]. The analyses conducted and the model validation on a considerably more extensive experimental material collected in the course of the experiments, for the particular evaporimeter pots and in the successive years of the study (Tab. 7–12), averaged values within the particular energy crop species (Tab. 13) and for selected years of the experiment (Tab. 14) demonstrated the flexibility of the model and its versatility. Analyses of the model parameters obtained through the calculations permitted the conclusion that the methodology adopted was justified, but required further perfection based on measurement data for an even longer period of time. The evaluations performed indicated that the three-year period of experimentation was still too short, and the results obtained indicate the necessity of verification on the basis of independent material acquired from measurements in consecutive years of experiment for the purpose of confirming the degree of their credibility. This will additionally permit the verification of the need and scope of modification of the model. The obtained values of relative errors of deviation of estimation of evpotranspiration of the particular energy crops indicate considerable reduction with increased degree of generalisation of the input data for the model. This can be seen in the results presented in the graphic representations of model fitting given in this work for various time intervals. The problem is a difficult one, and therefore field experiments are continued to increase the precision of fitting of the model for the particular energy crop species and to conduct an even more careful verification of the individual model parameters. The performed analyses of all the qualitative parameters of the model within the individual energy crop species indicate the need for constructing models grouping the energy crops with regard to the features, e.g. morphological. This can be observed in the analyses of model parameters α and β. The current sensitivity of the model to the variable weather conditions and even slight differences in the water content of the soil monolith profiles in the evaporimeter pots displays a broad spectrum through the variation of the calculated model parameters for all of the variants under analysis.

The need to create a possibility spatial interpretation of the results obtained for the purpose of elaboration of regional planning of cultivation of the energy crops used in the study on the basis of the developed WSMT model was why the study devoted to the verification of the capabilities of the model included also, as one of the input data, the diurnal values of reference evapotranspiration (ET_0) calculated with the use of the commonly available formula developed by Penman–Monteith. The results obtained show clearly that the diurnal sums of reference evapotranspiration (ET_0) calculated with the Penman–Monteith formula are a better component of the model input data than the measured diurnal sums of evaporation from open water surface. The parameter of quality of model fitting which indicates the choice of that factor is the relative error of deviation obtained from the calculations for all the variants. In a great majority of results obtained from calculations performed with the model it has lower values when that index is used. The factor which additionally supports the correctness of such an approach is the availability of the basic meteorological data entered as source data into the Penman formula and thus permitting the calculation of the diurnal values of reference evapotranspiration (ET_0) for any location. That approach will also permit the estimation of the possibility of generalisation of the model developed for a greater group of plant species grown for energy generation purposes, and the regional distribution of their cultivation.

9.1.1. Criteria of model evaluation

The evaluation of the model was made on the basis of the following indices: RRMSE (Relative Root Mean Squared Error), EF (Modelling Efficiency), CRM (Coefficient of Residual Mass), and the coefficient of determination. With the above indices we assume that O_i denotes observed values, P_i means predicted values obtained from the model, while $\bar{O}$ – mean value from the observed data.

Criterion EF (*Modelling Efficiency*) [Loague, Green 1991] compares the errors of predictions within the surroundings of the mean value of the measured parameter. As can be seen from the formula below, EF has no lower limit, while the highest value that it can assume is 1. Negative values of EF indicate poor fitting of the predictions to the measured value. This is expressed by the following formula:

$$EF = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2}$$

Another criterion of goodness of fit of the model to measurement data is RRMSE (*Relative Root Mean Square Error*) [Fox 1981, Bellocchi et al. 2002a]. That index can only assume positive values. It measures the mean relative deviations between values predicted by the model and actual values. Obviously, the closer the RRMSE value to zero the better the predictions relative to measurements.

$$RRMSE = \frac{\left(\sum_{i=1}^{n}(P_i - O_i)^2 / n\right)^{0.5}}{\bar{O}}$$

The last of the parameters used for the evaluation of the quality of the model developed was the relative error "*Bw*" calculated according to the formula:

$$Bw = \frac{1}{n}\left(\sum_{i=1}^{n}\left|\frac{P_i - O_i}{O_i}\right|\right) \cdot 100\%$$

The verification of the correctness of the model was performed through the determination of agreement of the predicted data with the values of evapotranspiration obtained experimentally. Tables 15 and 16 present the values of the measures of the model fit for the energy crop plants under study in the particular years of the experiment. For clarity, we wish to remind here that the averaging in question consisted in adopting for the calculations, as input data, the values of mean evapotranspiration for each day, from five evaporimeters, separately for each of the energy crop species studied, in the consecutive years of the field experiment. Comparative analysis of the results for the parameter "RRMSE" obtained with the use of values measured with evaporimeter EWP 992 and calculated with the application EVAPO indicates better quality of model fit with the application of the calculated data. This can be seen in the lower values of the index. The second index, "EF", in compliance with its concept also had higher values in a vast majority of cases analysed in that variant. The same tendency can also be observed in the evaluation of relative errors "Bw". As before, in a great majority of cases the values of that index were lower for the variant with EVAPO. Analysing the values of those parameters we can conclude that the fitting results obtained are satisfactory and close to the values of very good fitting of the model.

Table 15

Values of WSMT model fitting for averaged values in a year
for the energy crop species under study
Input data measured with EWP 992

Year	Plant	RRMSE	EF	Bw	R^2
2011	basket willow (*Salix viminalis*)	0.256	0.819	31.59	0.720
	Virginia mallow (*Sida hermafrodita* Rusby)	0.261	0.851	56.55	0.825
	giant miscanthus grass (*Miscanthus x giganteus*)	0.191	0.860	22.39	0.838
	Jerusalem artichoke (*Helianthus tuberosus*)	0.332	0.781	52.81	0.718
2012	basket willow (*Salix viminalis*)	0.206	0.834	29.66	0.801
	Virginia mallow (*Sida hermafrodita* Rusby)	0.285	0.795	28.06	0.745
	giant miscanthus grass (*Miscanthus x giganteus*)	0.161	0.846	16.53	0.818
	Jerusalem artichoke (*Helianthus tuberosus*)	0.244	0.768	24.60	0.699
2013	basket willow (*Salix viminalis*)	0.176	0.819	23.62	0.779
	Virginia mallow (*Sida hermafrodita* Rusby)	0.234	0.840	27.35	0.809
	giant miscanthus grass (*Miscanthus x giganteus*)	0.187	0.769	22.62	0.699
	Jerusalem artichoke (*Helianthus tuberosus*)	0.215	0.672	22.94	0.512

Table 16

Values of WSMT model fitting for averaged values in a year
for the energy crop species under study
Input data calculated with EVAPO

Year	Plant	RRMSE	EF	Bw	R^2
2011	basket willow (*Salix viminalis*)	0.197	0.893	31.84	0.880
	Virginia mallow (*Sida hermafrodita* Rusby)	0.203	0.911	41.04	0.902
	giant miscanthus grass (*Miscanthus x giganteus*)	0.200	0.847	26.72	0.819
	Jerusalem artichoke (*Helianthus tuberosus*)	0.299	0.823	59.45	0.785
2012	basket willow (*Salix viminalis*)	0.173	0.882	22.14	0.867
	Virginia mallow (*Sida hermafrodita* Rusby)	0.247	0.847	26.04	0.819
	giant miscanthus grass (*Miscanthus x giganteus*)	0.141	0.882	14.41	0.867
	Jerusalem artichoke (*Helianthus tuberosus*)	0.203	0.839	20.84	0.808
2013	basket willow (*Salix viminalis*)	0.151	0.866	19.41	0.846
	Virginia mallow (*Sida hermafrodita* Rusby)	0.200	0.883	18.73	0.868
	giant miscanthus grass (*Miscanthus x giganteus*)	0.156	0.839	17.17	0.808
	Jerusalem artichoke (*Helianthus tuberosus*)	0.177	0.779	21.15	0.540

9.2. Statistical models

The kind of tools applied, in the form of the mathematical apparatus for the analysis of the accumulated research material, depends to a significant degree on the amount of the material to be analysed. At the same time, the degree of recognition of processes and their mutual relations is another important factor determining the scope of application of the tools. Also in our case the large number of factors determining the process of evapotranspiration enforced the necessity of using methods adequate to the recognition of those relations, from the simplest to more complex ones, such as the model presented in the preceding chapter. In every mathematical model the phenomena or the results of field experiments are called observations and they are interpreted as values of various random variables whose probability distributions are often unknown and therefore the results obtained are subjected to statistical analysis. Observations are values of random variables, a random vector or a stochastic process [Magiera 2007]. Such a random variable is called an observable value of e.g. evapotranspiration, sum of atmospheric precipitation, air temperature, or water resources of soil. Statistical problems are characterised by the fact that the probability distribution of the random variable observed is not fully determined and we only know that it belongs to a certain family of distributions. Very often descriptive statistics is applied, dealing with the analysis of results of observations of a certain experiment, consisting in the determination of certain numerical characteristics of the data obtained, and in the presentation of a graphic frequency description of the nature of the observations. As opposed to mathematical statistics, the methods of descriptive statistics do not include concluding elements making use of the theory of probability [Magiera 2007]. The basic analysis of data usually comprises the determination of the numerical characteristics and the graphic presentation of the empirical distribution of the features under analysis. Extreme values are used as the numerical characteristics, ranges with high or low variation are determined, mean values are calculated, and median values and modal values are determined. The weighted mean can also be the mean for a sample. With large data sets it is also worthwhile to take into account the average deviation from the mean value, as well as information on the variance of the set under analysis. A broad spectrum of methods for the evaluation of research materials and conclusion drawing is given in the work [Magiera 2007]. In our study we applied the regression analysis, i.e. analysis of the stochastic relationship of one resultant variable – the values of evapotranspiration of the particular energy crops – to one or more independent variables in the form of a selected group of meteorological factors affecting the process of evapotranspiration. The analyses and experiments conducted demonstrated that a significant role was played by the relationships between the individual variables such as the analysed meteorological factors and the resultant variable of the values of evapotranspiration sums for various time intervals of the energy crops under study.

Independently from the deterministic model developed, it was decided to evaluate and test the possibility of estimation of evapotranspiration of the particular energy crops based on simpler forms of mathematical notation, using for the purpose the values of actual evapotranspiration obtained from measurements with soil evaporimeters, diurnal sums of atmospheric precipitation, air temperature, and measurements of soil moisture in the evaporimeters and outside of them. The measurement of soil moisture outside of the evaporimeters was obtained for the conditions of soil water functioning, i.e. for free flow of soil water in all directions. The use of information on soil water resources permitted the comparative analysis of the area evaporation calculated for the conditions of no water rise, as is the case in soil evaporimeters, and for the case of free access to ground waters, which is the case in natural conditions. Due to the fact that atmospheric precipitation is a phenomenon of a random character, basing just on information on soil water resources for various soil depths with one day time step for the estimation of evapotranspiration of plants would be insufficient and might lead to erroneous conclusions. The reason is too short period of time that is required for potential migration of water in the soil. It also results from the fact that usually – irrespective of the method of measurement – only changes of soil moisture at specific depths are monitored, and the water resources of the soil are determined by calculations for required soil layer thicknesses. This information is important as it demonstrates the limitations involved in the application of water balance calculations for such a short time period. Whereas, in the case of soil evaporimeters the factors described above are negligible because the evaporation of any amount of water from the soil monolith results in a change in its mass, which can be measured even for time intervals shorter than one day. The process of drying of the surface horizon of soil is affected by numerous factors, e.g. the time that elapsed since the last precipitation, its intensity, rate of water infiltration into the soil, that depends also on the state of soil saturation with water at the beginning of the period covered by the balance. Those processes should be analysed jointly, which is a considerable difficulty in the estimation of the effect of those factors on the process of evapotranspiration, and in the case of the presence of ground waters they should also be related to that agrometeorological element, as capillary rise appears under such conditions. The analyses of correlations conducted for one-day input data in the form of the meteorological elements proved to be of little significance, as due to the notable variation of the diurnal values it was not possible to obtain statistically significant correlations. It was only an extension of the time intervals that permitted the obtainment of interesting results.

9.3. Comparison of methods of estimation of energy crop plants evapotranspiration during their vegetation

The construction of simple relations between selected meteorological elements and diurnal sums of evapotranspiration of the particular energy crops demonstrated a lack of statistical significance of such relations. In that situation it was decided to use the diurnal sums of evapotranspiration in a somewhat different way and to analyse their variation cumulatively from the start of the field experiment in the successive years. That approach permitted the numerical and calendar identification of periods of intensified or weakened process of evapotranspiration of the particular energy crops, which is presented in Figures 45–47. Two methods of estimation of evaporation were adopted as reference for the values of evapotranspiration obtained from measurements with the soil evaporimeters. One of them was based on cumulatively calculated values of diurnal sums of evaporation from open water surface measured with evaporimeter EWP 992. The other method used also cumulatively calculated values of reference evapotranspiration (ET_0) determined for the particular days in consecutive years according to the “FAO–Penman–Monteith” formula. In 2011 the values of evaporation obtained with those two methods were close to each other over a major part of the vegetation period. In the second year of the experiment that similarity was observed only in the first half of the vegetation period, while in the further part of that period the differences remained at a constant level. In 2013 the differences were observable already at the start of the vegetation period and increased with the passage of time. The greatest differences between values measured in the evaporimeters and those adopted as the reference level can be noted for the data from 2012. Analysis of the runs of the sum curves constructed in that manner allowed to note a considerable variation of the sums of evapotranspiration in the particular pots as well as in the consecutive years of the experiment. Example runs of variability of increasing values of evapotranspiration from the particular evaporimeters, as well as the variation in the successive years of the experiment, are presented – for Virginia mallow – in Figures 45–47. The curves of the sums of evapotranspiration presented in the Figures indicate also the greatest variation in 2012, with distinct three groups, while the highest similarity of the curves can be noted for the data from 2013. In spite of the variation in the runs of the cumulative sums of evapotranspiration during the vegetation period in the particular years of the experiment, the total value of that index in the analysed evaporimeters and in the consecutive years did not exceed the level of 500 mm. Due to the fact that throughout the period of the experiment the same plants were in the evaporimeters, we could observe that the total value of evapotranspiration gradually decreased with the age of the plants.

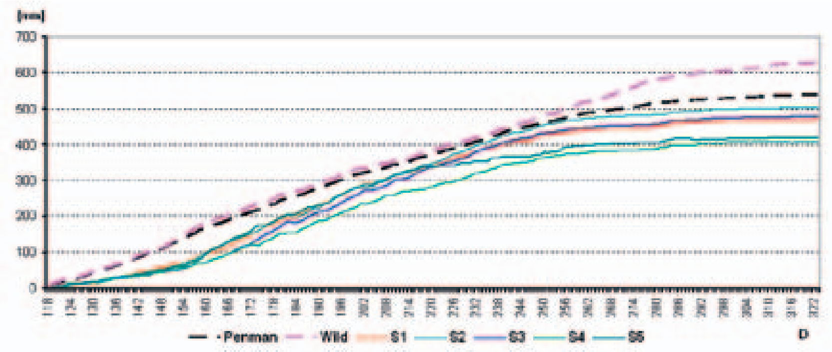


Fig. 45. Cumulated values of diurnal sums of index evaporation:
calculated – Penman–Monteith, measured with EWP 992 – Wild, and of evapotranspiration of Virginia mallow (*Sida hermafrodita* Rusby)
for particular evaporimeters – Ś1–Ś5 in 2011
Source: own elaboration

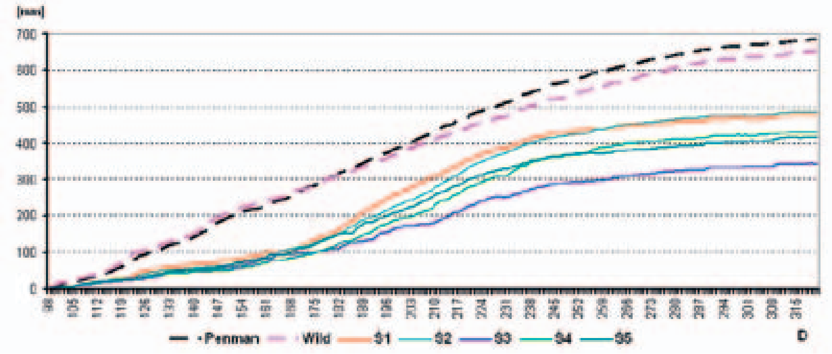


Fig. 46. Cumulated values of diurnal sums of index evaporation:
calculated – Penman–Monteith, measured with EWP 992 – Wild, and of evapotranspiration of Virginia mallow (*Sida hermafrodita* Rusby)
for particular evaporimeters – Ś1–Ś5 in 2012
Source: own elaboration

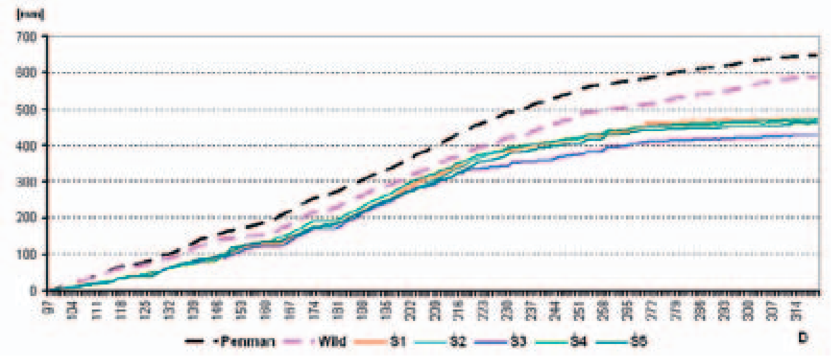


Fig. 47. Cumulated values of diurnal sums of index evaporation:
calculated – Penman–Monteith, measured with EWP 992 – Wild, and of evapotranspiration
of Virginia mallow (*Sida hermafrodita* Rusby)
for particular evaporimeters – Ś1–Ś5 in 2013
Source: own elaboration

9.4. Field water consumption and evapotranspiration

Field water consumption is a simplified method of estimation of water management by plants. The use of the method consists in balancing the water resources of soil and atmospheric precipitations in specific time intervals from an assumed moment and for a specific soil layer. To perform such a balance one needs to have at his disposal the results of measurements of soil water resources for a given thickness of the soil profile, and data on the diurnal sums of atmospheric precipitation. As during our experiment we conducted continuous monitoring of atmospheric precipitations and soil moisture in the evaporimeter pots and in the surrounding area under every energy plant, it was decided to employ that method for the purpose of comparison of the two methods. In the first variant we estimated the field water consumption in the evaporimeters, where the plants had no possibility of using ground water through capillary rise, and in the second – plants in the same canopy, but outside of the evaporimeters, where they had free access to water rising from the groundwater level. The soil evaporimeters had soil monoliths with depth of 70 cm. Therefore, to acquire information on the distribution of soil moisture in the evaporimeters TDR probes were placed in them at four depths (10, 20, 40 and 60 cm), which permitted the estimationm of water content in the entire monolith. For the same purpose, TDR probes were placed at the same depths also outside of the evaporimeter pots. The lowest depth of TDR robe placement was chosen based on our many years of experience. The experience indicates also that, apart from the classic dryer-gravimetric method, there is no possibility of continuous monitoring and data acquisition, as was the case in this experiment, to obtain a reliable estimate of soil water resources for small soil depths, i.e. less than 10 cm, using this method. Earlier attempts at placing probes at smaller depths indicated their poor stability in the soil, and thus caused considerable variation of the measurement results obtained, and raised doubts of the authors as to whether the measurement concerned soil moisture or soil air humidity.

For this reason, the minimum depth adopted in this experiment for TDR probe installation was 10 cm. That depth enforced also a second condition, i.e. the time step for which the calculations were made, as only the effects in the form of a change of moisture in the soil profile after considerable diurnal sums of precipitations, which occurred only sporadically during the whole of the three-year experiment, or several-day precipitations, were recorded at that depth. Those conditions determined the choice of a seven-day period as the final time period used in this case. That period resulted also from the frequency of performing the biometric measurements of biomass increments of the particular energy plants.

In that comparison, the groundwater table level, also monitored throughout the field experiment, proved to be an important parameter. In the first year of the experiment the groundwater table level was gradually lowering, starting from 110 cm on the 20th of May, 2011, to 147 cm below the ground surface on the 27th of June. From that date it started to rise successively until the 2nd of August, when it attained the value of 85 cm below ground level. That was the result of the considerable sum of precipitations noted during that period. During the period from the 27th of June till the 2nd of August a total 193.5 mm of rainfall was recorded. From the 2nd of August there was decreasing trend of the groundwater table, to the level of 137 cm below ground surface, observed in the middle of October. That situation was also accompanied by atmospheric precipitation, but with much smaller diurnal sums. The total amount of rainfall during that period was 123.0 mm.

In 2012 the changes of groundwater table level were somewhat different in character. On the 26th of May the groundwater level was 117 cm below ground surface. In spite of three events, when within a week from that date the influx of rainwater was about 40.0 mm each time, there was a systematic lowering of groundwater table and on the 20th of October, 2012, it attained the level of 163 cm below ground surface. Different still was the run of changes in groundwater table levels in 2013. High sums of precipitations appeared already in the last pentade of May and twice in June. In the period from the 25th of May till the 29th of June the sum of precipitations was 217.1 mm, which caused that in mid-June the groundwater table attained the level of 37 cm below ground surface. From that date, due to slight in turn atmospheric precipitation, there was a gradual drop of the groundwater table until the 7th of September when it attained the level of 141 cm. From that date to the 17th of September, i.e. within just 10 days, a considerable – for the season – sum of precipitations was recorded, amounting to 86.4 mm. This was the turning point and thenceforth the groundwater levels started to rise successively. The next sum of precipitations, 27.8 mm noted during the period from the 20th to the 28th of September, did not cause any acceleration in the rise of the groundwater table level. On the 5th of October it attained the highest level – 93 cm below ground surface, and then the groundwater table began to lower again. The presented changes in the levels of the groundwater table in three vegetation seasons permit the estimation of the possibility of using, during those periods, capillary rise water by the energy plants growing outside of the evaporimeter pots. At the same time, the considerable sums of precipitation in short periods of time did not permit a "smooth" replenishment of the soil water resources, but they did contribute to an increased outflow from the soil monoliths of the evaporimeters.

The results of calculations of the field water consumption, obtained according to the criteria and for the periods given at the beginning of this chapter, were compared with the values of the actual evapotranspiration calculated from the diurnal sums for the same periods as those used in the calculations of field water consumption, that is for weeks. The effects of the calculations are presented in graphic form in Figures 48–51. The point data obtained in that manner are often considerably scattered, and for clarity of the results obtained it was decided to describe them by means of equations in the presented Figures. That operation was performed separately for each of the energy plants. Within the individual years of the experiment, the runs of values obtained for the weekly sums of evapotranspiration of the particular energy crops and field water consumption were described by means of equations and corresponding coefficients of determination for the variant with access to ground water and for the conditions of eliminated capillary rise for plants in the soil evaporimeters. Analysis of the coefficients of determination calculated for common osier, Virginia mallow, giant miscanthus and Jerusalem artichoke for the years 2011–2013 indicates that only in two cases, i.e. in 2011 and 2013 on the area with giant miscanthus the values of that parameter proved to be statistically insignificant. In 2011 that concerned the plants on the plot, while in 2013 – those in the evaporimeter pots (Fig. 50). Comparative analysis of the values of the coefficient of determination obtained for the four energy crops used in the field experiment in the period of 2011–2013 revealed that in a great majority of cases the values related to the run of the sums of measured actual evapotranspiration of the particular energy crops. The exceptions were giant miscanthus in 2012 with $R^2 = 0.4122$ (Fig. 50) and Jerusalem artichoke in 2011 with $R^2 = 0.3458$ (Fig. 51). As concerns the run of field water consumption calculated for the variant with capillary rise, it can be noted that the coefficients of determination obtained were at the lowest level among the three runs analysed in each of the years. High values of that index were obtained only four times. In 2011 – at the level of $R^2 = 0.4859$, and in 2012 – $R^2 = 0.4865$, for Jerusalem artichoke and Virginia mallow, respectively (Fig. 49 and 51). Similar level of values of that index were obtained in 2012 – $R^2 = 0.4865$ and 0.4356, for common osier and giant miscanthus, respectively (Fig. 48 and 50). The diversity of the values of coefficients of determination for that variant in 2012 indicates that the variation in the field water consumption resulted from the different water management by the particular energy crops. The groundwater table in that year had no effect as from the start of the vegetation period it was on low levels – on the 25th of May it was 117 cm below ground surface and tended to lower over the whole period of vegetation. In 2013, in turn, the values of the coefficient of determination for that variant were stable (Fig. 48–51) in spite of high levels of groundwater table over a major part of the vegetation period and their considerable variation. Analysis of the character of the shapes of the curves and the kind of equations describing the variation of field water consumption for both variants indicates in many cases a similar character of the runs and an identical form of equations describing them, i.e. quadratic polynomials. In the case of Virginia mallow and Jerusalem artichoke in 2011 and Jerusalem artichoke in 2013 the run of field water consumption in the variant with access to ground waters is described by means of exponential equations. Analysis of the runs of actual evapotranspiration and field water consumption for both variants for the year 2011 (Fig. 48–51) indicates that a very high similarity was observed for all three curves only in the case of giant miscanthus, the highest value of the coefficient of determination being obtained for the curve describing evapotranspiration – $R^2 = 0.702$. In 2012 similarity in the shapes of curves describing the three variants mentioned above can be noted for osier and Virginia mallow. For miscanthus the curve describing the run of field water consumption in the variant with no capillary rise differs notably at the start of the vegetation period, while in the case of Jerusalem artichoke its shape is completely different from the other two curves. In 2013 we can note a very high similarity in the shapes of curves describing field water consumption, both for the variant with capillary rise and for the variant with no capillary rise (plants in evaporimeter pots). This related to all of the energy crop under study.

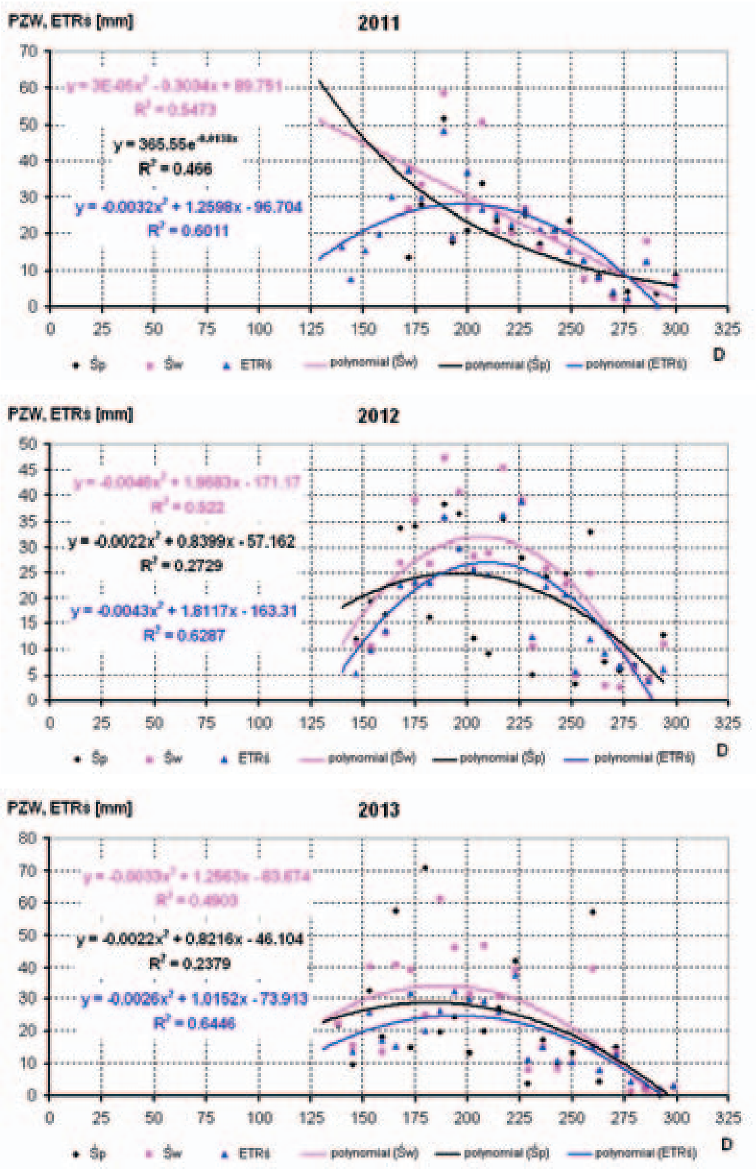


Fig. 48. Variation of field water consumption (PZW) and evapotranspiration (ETRw) of common osier (*Salix viminalis*) in vegetation periods in 2011–2013
Wp – common osier on plot, Ww – common osier in soil evaporimeter,
D – consecutive day of the year

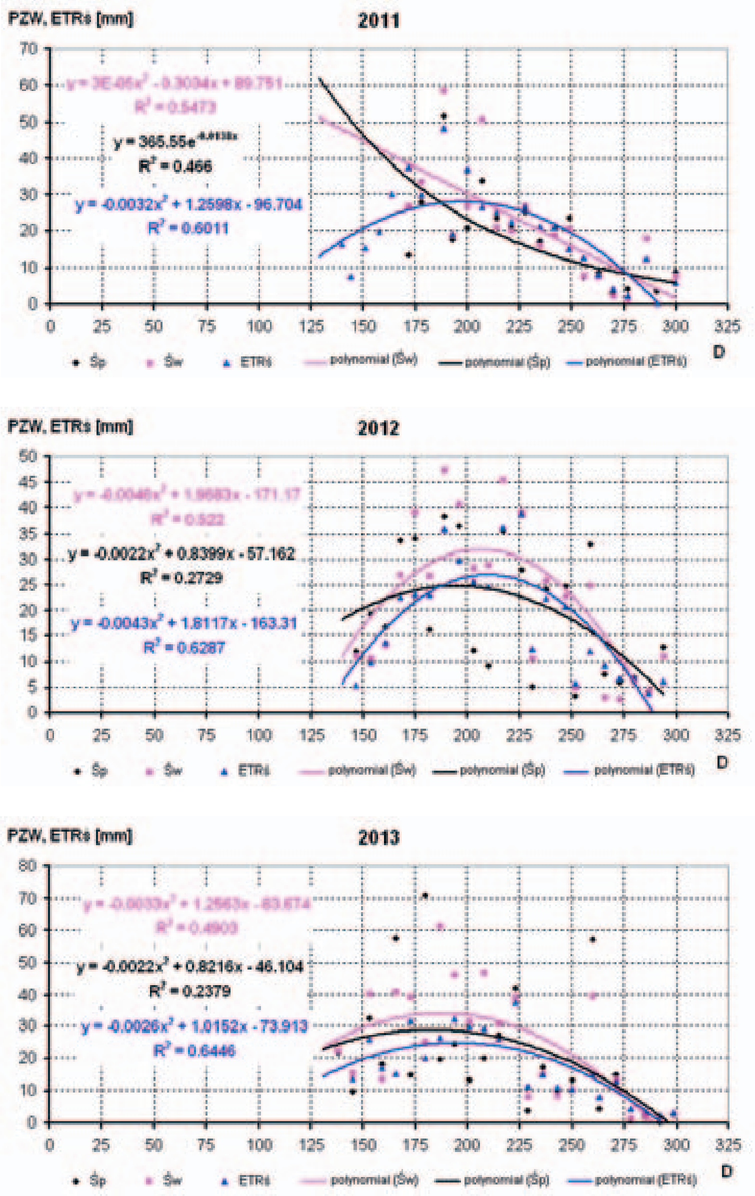


Fig. 49. Variation of field water consumption (PZW) and evapotranspiration (ETRś) of Virginia mallow (*Sida hermafrodita* Rusby) in vegetation periods in 2011–2013
Śp – Virginia mallow on plot, Św – Virginia mallow in soil evaporimeter,
D – consecutive day of the year

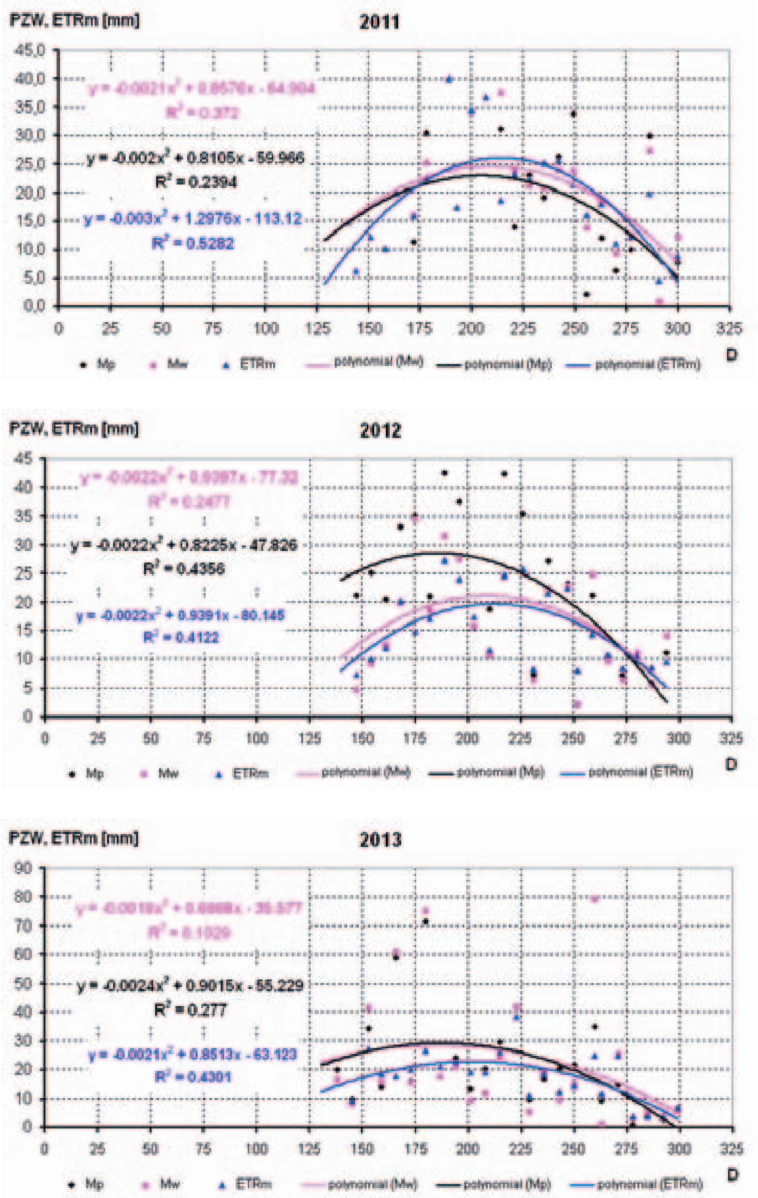


Fig. 50. Variation of field water consumption (PZW) and evapotranspiration (ETRm) of giant miscanthus (*Miscanthus x giganteus*) in vegetation periods in 2011–2013
Mp – giant miscanthus on plot, Mw – giant miscanthus in soil evaporimeter,
D – consecutive day of the year

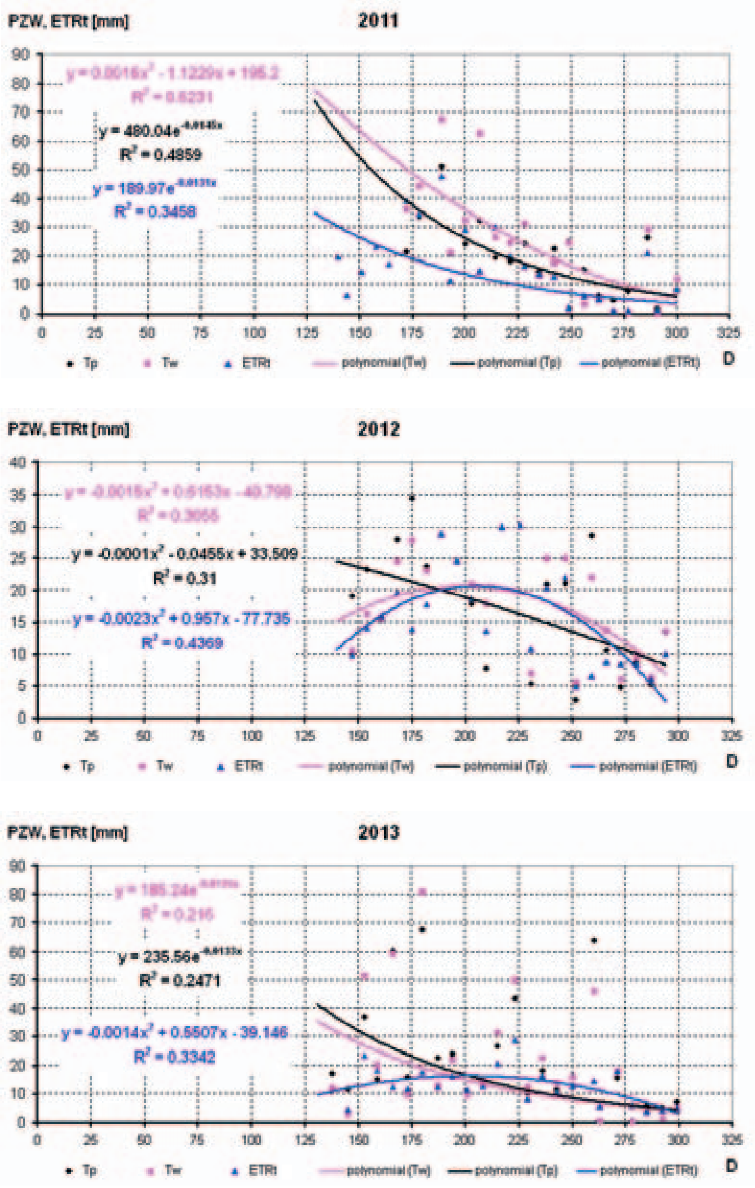


Fig. 51. Variation of field water consumption (PZW) and evapotranspiration (ETRt) of Jerusalem artichoke (*Helianthus tuberosus*) in vegetation periods in 2011–2013
Tp – Jerusalem artichoke on plot, Tw – Jerusalem artichoke in soil evaporimeter,
D – consecutive day of the year

9.5. Relation of evapotranspiration of the energy crops with selected meteorological factors for various time intervals

The process of evapotranspiration is highly complex. Most frequently the formulae describing it contain elements characterising energy input, water resources in atmospheric air, and a description of the dynamics of the atmosphere in the form of wind velocity. At present there are very many formulae describing the process of evapotranspiration, a vast majority of which relating to local conditions. One of them, the "FAO–Penman-Monteith" formula proved to be the one which has found a common application in the world. Thanks to its quality, it now functions in the world as the reference method. For this reason we decided to take advantage of its versatility, and of the fact that in the course of realization of the experiment described in this monograph the software tool "EVAPO" was developed [Chieng et al. 2012], providing a simple method of calculation of evapotranspiration for one-day time intervals. Having the results of diurnal observations of evapotranspiration obtained from the evaporimeter measurements for the particular energy crops for entire vegetation seasons of the consecutive years, and the values of reference evaporation calculated with the Penman–Monteith method, we determined the relations between those two variables. Examples of the relations for Virginia mallow are presented in Figures 52–54. The general notation in the form of regression equations was not satisfactory, although the relations obtained proved to be statistically significant. A notable scatter of points can be seen in all of the cases presented. The character of the shapes of the curves obtained, in spite of the similar values of the coefficient of determination, indicates differences between the relations obtained for the particular years. Those resulted primarily from diversified weather conditions in the years of the field experiment. However, the formulae permit the estimation of the actual evapotranspiration, in this case for Virginia mallow, for one-day time intervals. The large variation of actual evapotranspiration, with identical values of evapotranspiration calculated with the Penman–Monteith formula, indicates the justifiability of determining the same relations but for longer time steps. By analogy to the biometric measurements, calculations were performed as presented in Figure 55. Independently from the determination of the relations in the particular years, that operation was performed also for the entire set of input data accumulated during the period of the experiment. At the first glance one can note the different character of the mathematical formulae describing those relationships in the particular years, and what is most interesting there is a visible improvement of the coefficient of determination. The extension of the time step resulted in nearly doubled values of that index relative to the relationships determined for the one-day intervals, and in low variation in the particular years (Fig. 55). Also the relationship determined for the entire period of 2011–2013 is similar in character and its coefficient of determination does not differ much from those obtained for the particular years.

Air temperature is a meteorological element commonly used in the estimation of various phenomena in the natural environment, as well as a factor used for the description of weather conditions in field experiments. It is also used in very many other areas, hence it is a meteorological element that is generally accessible. The authors decided to make use of that possibility for the estimation of the values of evapotranspiration of the ener-

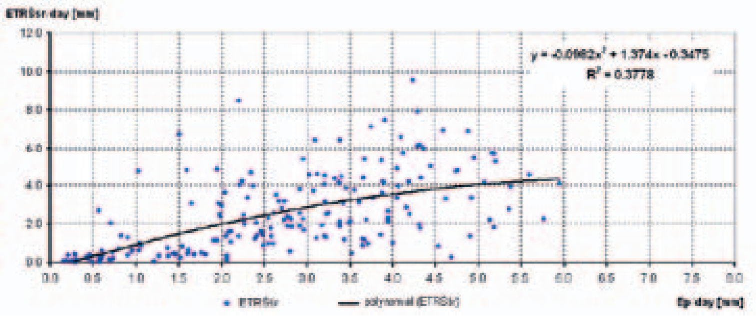


Fig. 52. Relation of diurnal sums of evapotranspiration ETRśśr
of Virginia mallow (*Sida hermafrodita* Rusby) to diurnal sums of reference evapotranspiration
calculated with the Penman–Monteith formula – Ep, in 2011. Source: own elaboration

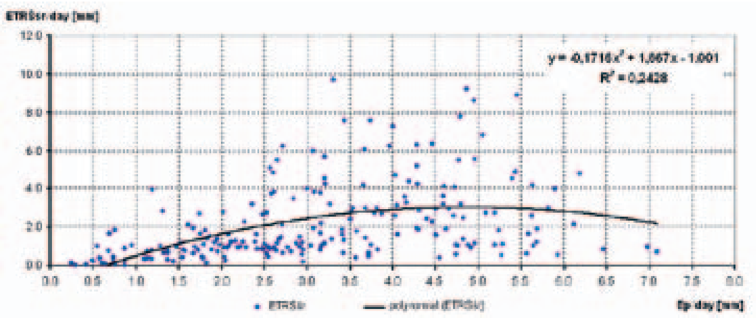


Fig. 53. Relation of diurnal sums of evapotranspiration ETRśśr
of Virginia mallow (*Sida hermafrodita* Rusby) to diurnal sums of reference evapotranspiration
calculated with the Penman–Monteith formula – Ep, in 2012. Source: own elaboration

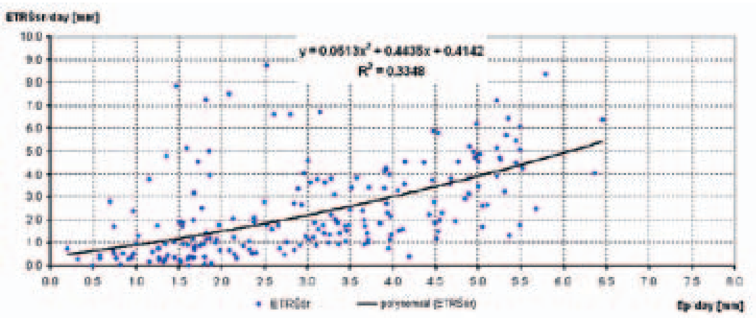


Fig. 54. Relation of diurnal sums of evapotranspiration ETRśśr
of Virginia mallow (*Sida hermafrodita* Rusby) to diurnal sums of reference evapotranspiration
calculated with the Penman–Monteith formula – Ep, in 2013. Source: own elaboration

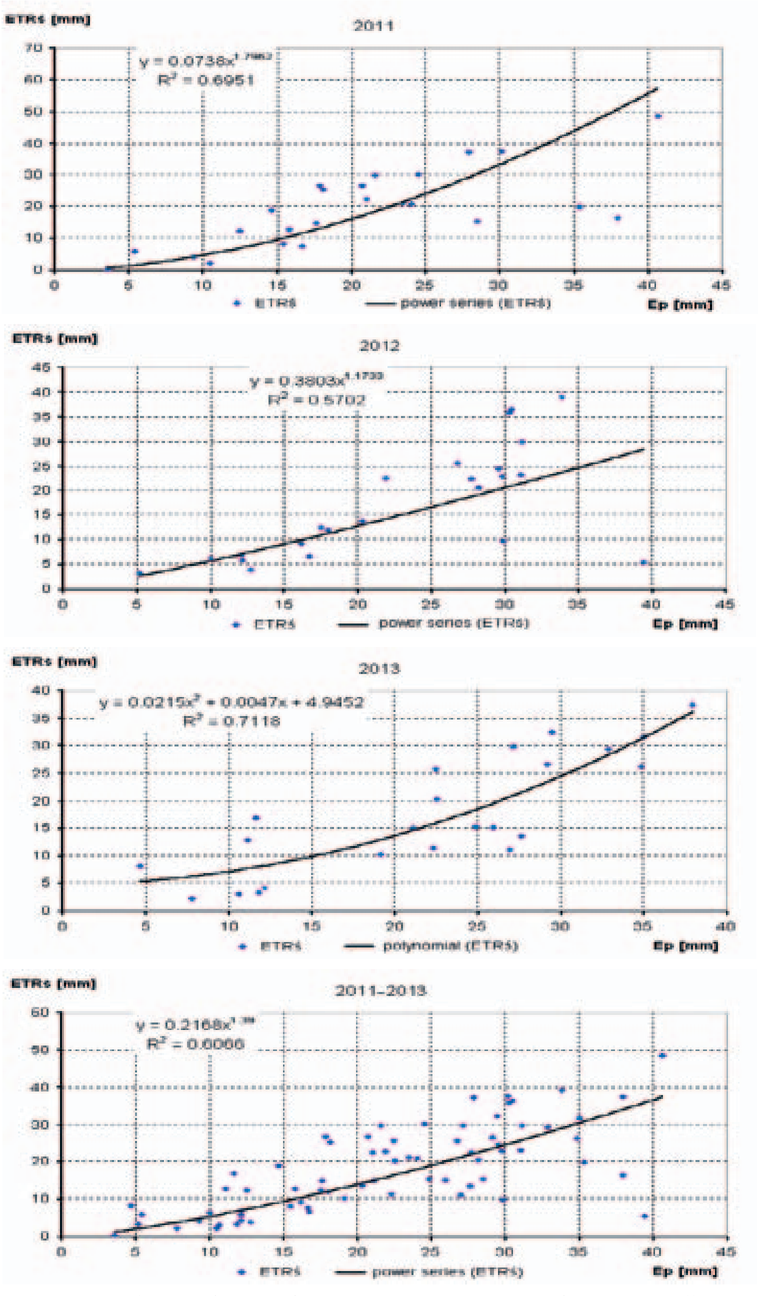


Fig. 55. Relation of sums of evapotranspiration ETRś of Virginia mallow (*Sida hermafrodita* Rusby) for periods between biometric measurements to sums of reference evaporation calculated with the Penman–Monteith formula – Ep for analogous periods in the years 2011–2013 and for the entire period of 2011–2013. Source: own elaboration

gy crops in the experiment. To built the progressions of the sums of air temperature from the start of vegetation in the successive years of the field experiment, the sums of mean diurnal air temperature for the periods between the particular dates of biometric measurements were used as the input data. The sums of evapotranspiration of the particular energy crops were calculated in an analogous manner. The mutual relations of the two parameters, on the example of Virginia mallow, are presented in Figure 56. The index of quality, as in the previous analyses, was the coefficient of determination. Its values for Virginia mallow, both in the particular years and for the entire period of the experiment, are at a high and uniform level (Fig. 56). The good results obtained in the analyses performed by then motivated the authors to conduct estimations of the relations between cumulative sums of evapotranspiration of the energy crops included in the field experiment and the cumulative sums of air temperature, but for periods longer than 24 hours. In scientific literature the pentade periods are frequently employed, so it was decided to determine those relations for five-day periods.

As in the analyses presented earlier, the graphic image of the relations determined is presented only for one of the analysed energy crops, in this case common osier (Fig. 57). The results presented in the Figure illustrate the relations of the cumulative, from the start of vegetation, pentade sums of actual evapotranspiration of common osier to the cumulative pentade sums of air temperature in the particular years of the experiment. Only in 2011 one can note a deviation of the values obtained from measurements and balance in the form of a regression curve. However, the values of the coefficients of determination for all the years indicate a high correlation between both of the indices under analysis. Comparative analysis of the results obtained for the relationships based on the cumulative values of both parameters, for the 24-hour as well as the pentade time steps, gives equally satisfactory effects.

Such relationships for the 24-hour time step were analysed also in relation to evaporation from bare soil surface and grass covered soil, adopted as standard in agrometeorology. The results obtained in the form of calculated coefficients of determination for correlation with evaporation from bare soil surface in the years 2012 and 2013 were notably higher for all four energy crops than those obtained for the relations with evaporation measured with the Wild evaporimeter and with evaporation estimated with the Penman–Monteith method. In support of this information we inform that in 2012 the coefficients of determination R^2 concerning the relation of evapotranspiration in evaporimeters to evaporation estimated with the Penman–Monteith method varied in the range from 0.1393 for miscanthus to 0.2419 for osier. Whereas, for the relations with evaporation from bare soil surface they varied from 0.465 for osier to 0.6572 for miscanthus. The analogous relations for 2013 varied from 0.0349 for Jerusalem artichoke to 0.3348 for Virginia mallow. The coefficients of determination calculated for that year for the relations with evaporation from bare soil surface were more stable and varied from 0.3547 for Virginia mallow to 0.5464 for osier. Notably poorer results were obtained for the relations with area evaporation from grass-covered soil surface. In both years in question the coefficients of determination were at a low level and varied in 2012 within the range from 0.0277 for miscanthus to 0.0953 for osier, and in 2013 – from 0.0429 for Jerusalem artichoke to 0.0996 for osier. In confrontation with those results, decidedly

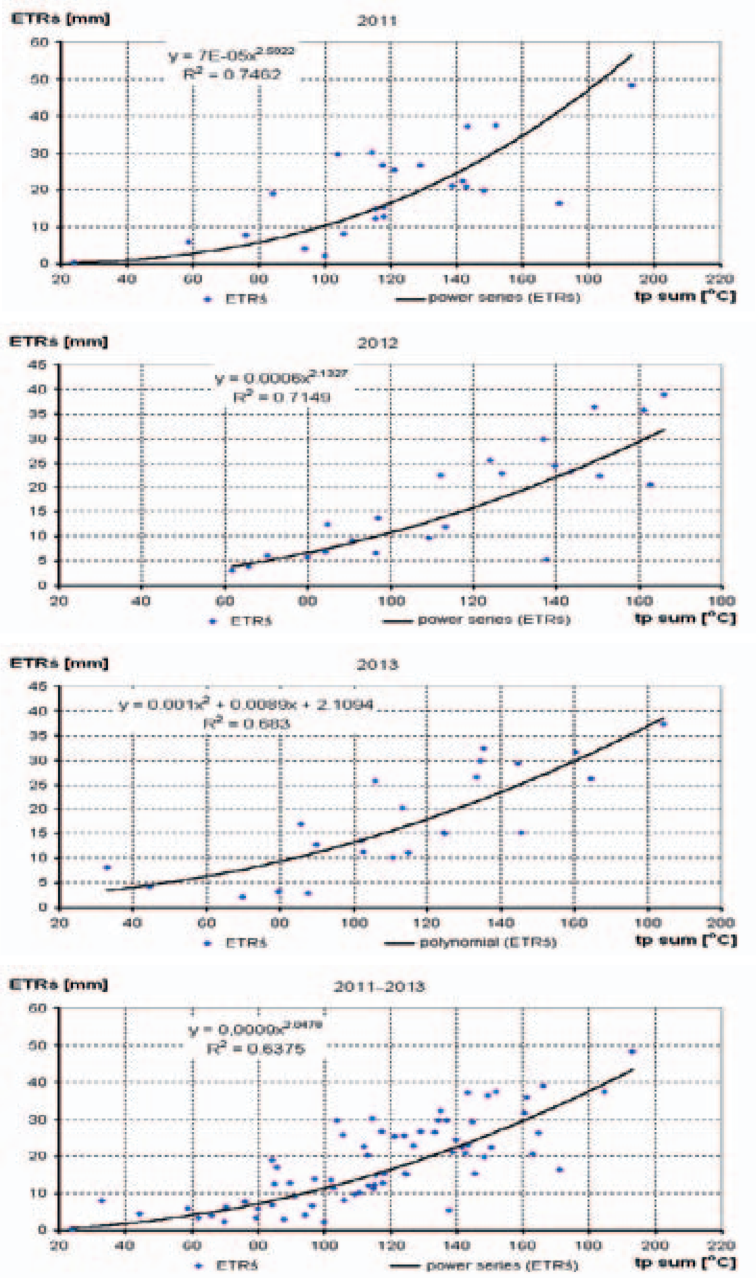


Fig. 56. Relation of sums of evapotranspiration ETRś of Virginia mallow (*Sida hermafrodita* Rusby) from periods between biometric measurements to sums of air temperature – tp sum for analogous periods, in the years 2011–2013 and for the entire period of 2011–2013. Source: own elaboration

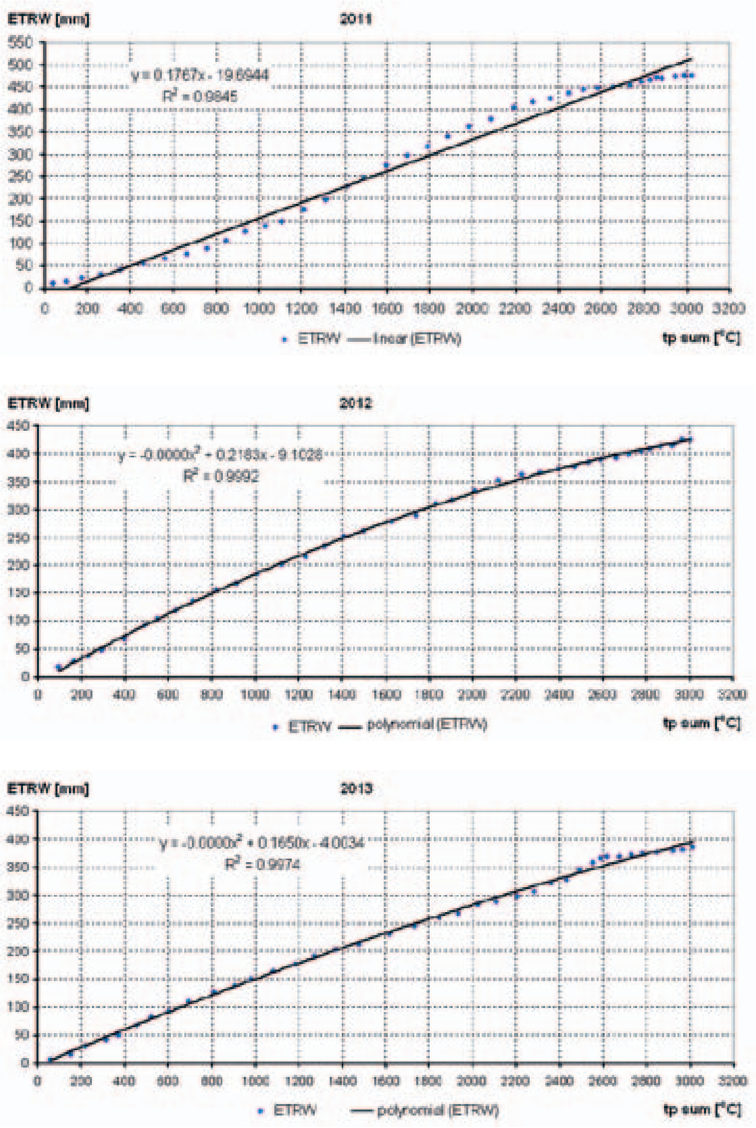


Fig. 57. Relations of cumulative pentade sums of evapotranspiration ETRW – of common osier (*Salix viminalis*), calculated from the beginning of May, to cumulative sums of air temperature for the same period, in the years 2011–2013. Source: own elaboration

the best relations of field evaporation measured with the soil evaporimeters, for all energy crops studied and in all the years of the field experiment, were obtained for the variant with the sums of field evaporation from the measurements and the values of index evaporation estimated with the Penman formula.

The results obtained in the study permitted also an overall estimation of all correlations elaborated for the relations based on sums calculated for the periods between the weekly biometric measurements, taking into account all four energy crops under study. Such analyses were conducted with the use of the measured or calculated diurnal values of the selected agrometeorological elements. They consisted in the calculation of correlations between sums of field evaporation from the soil evaporimeters and sums of references evaporation estimated with the Penman–Monteith formula, sums of evaporation from open water surface measured with the Wild evaporimeter, mean air temperatures and sums of air temperatures. The calculations performed and analyses of the results obtained permit the conclusion that the best results, for that time interval, were obtained for the relations of field evaporation of the particular energy crops, measured in the soil evaporimeters, with the references evaporation estimated with the Penman formula and with the sums of air temperatures. The resultant coefficients of determination R^2 are high – in all of the years of the experiment. In 2011 the highest value of that index for the first of those elements was obtained for Virginia mallow – 0.6951, while in 2012 and 2013 the highest values were obtained for common osier – 0.7688 and 0.8954, respectively. The highest values of the coefficient of determination R^2 for the relations of field evaporation of the energy crops with the sums of air temperatures, in all the years, were obtained for Virginia mallow. The values varied from 0.683 in 2013 to 0.7462 in 2011. The third ranking agrometeorological element, in terms of the significance of the calculation results obtained, were the values of mean air temperature calculated for the periods between the biometric measurements. The coefficients of determination obtained for that index indicated a notable stability in the successive years of the experiment, attaining values from 0.6621 in 2011, 0.6677 in 2012 and 0.6792 in 2013. Whereas, the worst results were obtained in the relations of field evaporation from the soil evaporimeters with the values of evaporation from open water surface measured with the Wild evaporimeter. The highest values of the coefficient of determination were obtained in the years 2011 and 2013, at 0.3537 and 0.5635, respectively, for Virginia mallow, while in 2012–0.6398 for common osier.

In addition, an estimation of those relations was made for the entire three-year period of the experiment. The coefficients of determination obtained in that way demonstrated that the highest correlations among the four energy crops studied, in all the variants, were obtained for Virginia mallow. The values of the coefficient varied from 0.3187 for the relation with evaporation from open water surface, through 0.6066 for the relation with references evaporation estimated with the Penman–Monteith method, to 0.6375 for the relation with the sums of air temperatures.

10. Empirical indices for the estimation of evapotranspiration of selected energy crops

The methods of estimation of actual evapotranspiration presented in the preceding chapters for four energy crops, i.e. giant miscanthus, Virginia mallow, common osier and Jerusalem artichoke, based on easily available meteorological data and on the results of measurements of evaporation from open water surface with the Wild evaporimeter and of the references evaporation estimated with the Penman–Monteith formula, permitted the acquisition of information concerning the applicability and the ranking and quality of the input data applied. The results obtained, in spite of the short period of the experiment, allow those methods to be used for spatial estimation of actual evapotranspiration of those crop plants under diverse meteorological conditions, as the spatial information on e.g. the values of diurnal sums of atmospheric precipitation or the mean diurnal air temperature is easily available. Whereas, the realization of calculations of the index evaporation with the Penman–Monteith formula is also simplified, as the authors of this monograph, in the course of the studies, developed a software tool, "EVAPO", permitting easy acquisition of information on evapotranspiration for the 24-hour time step. As mentioned earlier, that tool is described in detail in the publication by Chieng et al. [2012]. Another important factor permitting the spatial interpretation of the results obtained is the fact that the field experiment was conducted on light soils which, according to various sources, account for over 60% of soil in Poland. However, due to the difficulties involved in the acquisition of measurement data on the evapotranspiration of various plants directly from field measurements, in the literature one can often encounter the use of various empirical indices permitting the estimation of that parameter on the basis of evaporation from open water surface or reference evaporation estimated with the method developed by Penman–Monteith and treated as a reference method. Taking this into account, the authors of this monograph also developed empirical indices permitting the estimation of evapotranspiration of giant miscanthus, Virginia mallow, common osier and Jerusalem artichoke. The averaged empirical coefficients *k* for the particular years of the study (2011–2013) are given in Tables 17 and 18. The first of the Tables presents the values of the empirical indices calculated for one-week periods corresponding to the frequency of the biometric measurements, while Table 18 gives the values of the empirical coefficients for the commonly used time interval i.e. the decade. Each of the Tables includes two variants which permit the calculation of evapotranspiration of the test energy crops on the basis of the reference evaporation either measured with the Wild evaporimeter or estimated with the Penman–Monteith method, where:

$$k = \frac{ETR}{Ep} \quad \text{or} \quad k = \frac{ETR}{Ew} \; .$$

Table 17

Mean values of the empirical coefficients “*k*” for the period of 2011–2013
for the calculation of evapotranspiration of selected energy crops with the possibility
of using reference evaporation calculated with the Penman–Monteith formula – *Ep*
or evaporation from open water surface measured with EWP 992 – *Ew*

D	$ETR = k \cdot Ep$				$ETR = k \cdot Ew$			
	W	Ś	M	T	W	Ś	M	T
139								
145	0.552	0.335	0.287	0.263	0.519	0.315	0.270	0.247
153	0.716	0.553	0.527	0.599	0.768	0.593	0.566	0.643
159	0.811	0.808	0.649	0.902	0.830	0.826	0.664	0.922
166	0.859	1.112	0.832	0.839	0.988	1.278	0.957	0.965
173	0.760	0.921	0.521	0.629	0.815	0.988	0.559	0.675
180	0.899	1.205	0.985	1.043	0.948	1.271	1.039	1.100
188	0.703	1.098	0.841	0.790	0.798	1.247	0.955	0.897
194	0.860	1.111	0.859	0.763	0.979	1.264	0.978	0.868
201	0.943	1.154	0.927	0.740	0.971	1.188	0.954	0.762
208	0.780	1.025	0.846	0.587	0.893	1.173	0.968	0.672
215	0.835	1.039	0.810	0.890	0.985	1.226	0.955	1.050
223	0.874	1.030	0.908	0.854	0.984	1.159	1.022	0.961
229	0.805	0.955	0.757	0.662	0.943	1.118	0.886	0.774
236	0.996	0.775	0.893	0.665	1.098	0.855	0.985	0.734
244	0.748	0.682	0.769	0.567	0.759	0.691	0.780	0.575
250	0.698	0.687	0.880	0.493	0.647	0.638	0.816	0.458
258	0.693	0.620	0.906	0.414	0.621	0.556	0.812	0.371
264	1.198	0.777	1.175	0.660	0.934	0.606	0.916	0.514
271	0.935	0.660	1.290	0.706	0.675	0.476	0.931	0.509
278	0.385	0.350	0.708	0.422	0.257	0.233	0.473	0.282
286	0.631	0.534	0.849	0.894	0.469	0.397	0.631	0.665
292	0.678	0.453	0.911	0.755	0.512	0.343	0.689	0.570
300	0.537	0.439	0.811	0.633	0.497	0.406	0.751	0.586

Table 18

Decade values of the empirical coefficients “k” for the period of 2011–2013 for the calculation of evapotranspiration of selected energy crops with the possibility of using reference evaporation calculated with the Penman–Monteith formula – Ep or evaporation from open water surface measured with EWP 992 – Ew

month	decade	ETR = k·Ep				ETR = k·Ew			
		W	Ś	M	T	W	Ś	M	T
V	3	0.656	0.454	0.419	0.457	0.663	0.459	0.424	0.461
VI	1	0.735	0.848	0.687	0.792	0.791	0.913	0.739	0.853
	2	0.875	0.977	0.649	0.758	0.955	1.066	0.708	0.827
	3	0.814	1.184	0.895	0.945	0.903	1.313	0.993	1.048
VII	1	0.782	1.115	0.813	0.727	0.852	1.215	0.886	0.792
	2	1.003	1.178	0.981	0.859	1.049	1.233	1.027	0.899
	3	0.786	1.016	0.834	0.722	0.945	1.222	1.004	0.869
VIII	1	0.832	1.011	0.857	0.807	0.942	1.145	0.970	0.914
	2	0.898	0.899	0.785	0.706	1.016	1.018	0.888	0.799
	3	0.807	0.692	0.830	0.557	0.843	0.723	0.867	0.582
IX	1	0.657	0.579	0.774	0.471	0.587	0.518	0.691	0.421
	2	1.000	0.800	1.189	0.527	0.854	0.684	1.016	0.450
	3	0.764	0.571	1.099	0.624	0.550	0.411	0.791	0.449
X	1	0.526	0.421	0.750	0.628	0.357	0.286	0.508	0.426
	2	0.673	0.538	0.956	0.917	0.538	0.430	0.764	0.733
	3	0.412	0.269	0.714	0.412	0.349	0.227	0.605	0.348

Explanations for Tables 15 and 16:

D – day number in the year, Et – Evapotranspiration of selected energy plant,
W – common osier (*Salix viminalis*), Ś – Virginia mallow (*Sida hermafrodita* Rusby),
M – Giant miscanthus (*Miscanthus x giganteus*), T – Jerusalem artichoke (*Helianthus tuberosus*)

11. Biomass productivity

The intensity of the process of evapotranspiration of energy crops is significantly related with biomass productivity, which is highly important information for the producers of biomass and for the recipients of biomass for energy generation purposes. Usually the basic and most frequently acquired information is that which concerns the amount of biomass on a plantation, e.g. at the end of the vegetation period. The collaboration of producers of energy crops with biomass recipients in the region of its cultivation enforces the acquisition of information on the current amount of biomass on a plantation throughout the period of vegetation. For this reason many research centres have been conducting for years work on the development of mathematical model permitting the estimation of biomass yield from energy crops. Generally they can be classified as empirical models and mechanistic models. The former make use of data from direct measurements and aim at identifying relations between the yields of energy crops and selected meteorological and soil factors, and cultivation treatments. Whereas, the mechanistic models consist in correlating the physiological and morphological traits that determine plant growth. Those models include models directly dedicated for energy crop cultivations and adaptations of existing models of plant yielding. In their majority those models require a lot of good-quality and hard to obtain input data concerning, among other things, the phenological phases, the dynamics of leaf area increase, selected meteorological data, and data on the cultivation treatments applied, that are often hard to acquire. For this reason the authors of this monograph, whose earlier research concerned the problems of modelling of the yields of various crop plants (e.g. spring wheat and potato) [Szulczewski et al. 2012, Żyromski et al. 2013], undertook activities aimed at the development of an innovative model for the estimation of the current amount of biomass that can be obtained from a plantation of common osier and Jerusalem artichoke in the course of their vegetation.

The method developed is an innovative approach to the estimation of potential yields of biomass of specific energy crops, and the information can be obtained at any desired moment during their vegetation period and does not require specialist measurements and analyses involving the use of expensive measurement apparatus. The method proposed was developed on the basis of results of a field experiment. As the experimental plots were established in 2010, the model of biomass increments was developed on the basis of results of measurements conducted on the energy plants in the years 2011–2013 (2nd–4th year of plantation). Their cultivation was conducted with the extensive method. In the years adopted for the analyses, varied numbers of plants started their vegetation – 364 in 2011, 347 in 2012 and 348 in 2013, respectively. The method developed is based only on results from simple biometric measurements that can be conducted by the farmers themselves, practically with financial outlays and no major disturbances on the plantations. On that basis a calculator was designed, calculating the current amount of biomass on a plantation. The estimations can be made both in the course of vegetation and after its end. They are performed with a predetermined probability, and the estimated amount of biomass is obtained with an accuracy determined by the model, depending on the number of stems measured. The results obtained permit the estimation of the current amount of biomass on a plantation at any given time in the vegetation season. Information obtained in that was can be used for the estimation of possibilities of meeting the demand of specific biomass recipients for energy purposes.

The biometric measurements conducted in the vegetation periods of common osier in the years 2011–2013 were aimed at the determination of its growth dynamics. They included all the plants, except for those growing in the outer rows on the plot perimeter, those being treated only as shelter belts. The first operation consisted in periodic cutting, from plants not included in the biometric measurements, of random-chosen individual shoots with length greater than 0.5 m. The next operation was the measurement of the length h_i of i-th shoot cut, its diameter d_i in the middle of its length, and then each of the shoots cut was weighed to determine the mass x_i of the individual shoots. Every time the samples were composed of a similar number of shoots, and taken at regular time intervals. For each shoot its volume index was determined:

$$y_i = \frac{1}{3}\pi d_i^2 h_i$$

In this study the volume index is used instead of the shoot volume, as the mass measured includes both the mass of the stem and of the leaves on the stem. The total numbers of shoots that were cut and described as above over the entire vegetation periods were 192 shoots in 2011, 166 shoots in 2012, and 175 shoots in 2013. The second type of measurement consisted in non-destructive biometric measurements conducted each time on the same 5 shrubs of common osier at one-week intervals. The biometric measurements were started when the plants on the plot attained the height of 0.5 m. Every time the number of shoots in a shrub was counted, and the length and mid-point diameter of 3 selected (each time the same) and marked shoots were measured. That information is given in chapter 6.2 concerning the methods used in the field experiment.

It was assumed that the distributions of the number, diameter and mass of shoots are parameters characteristic for a given plant species. Based on those parameters it was found out that the mass of shoots on a field is best described by the Pascal distribution. This permits the calculation of the value of expected mass of shoots on any given area. Based on that distribution a static model was obtained, describing the mass of the plants. The extension of the model to a dynamic model permitted the estimation of the amount of biomass at any moment during their vegetation. The results obtained permit dynamic estimation of the amount of biomass. The preliminary results indicate the need of taking 15 shoots from 5 freely chosen plants for the estimation of the amount of biomass.

Due to the fact that the method was developed on the basis of a short, only three-year, period of experiment, it is necessary to verify it on independent research material that will permit more precise determination of the number of shoots required for a global estimation for a freely chosen time during the period of vegetation. In the case of area estimates it is also necessary to take into account the density of plants per unit surface area.

The model for the estimation of biomass, discussed above, was developed on the basis of results obtained in the course of the field experiment and through logical and mathematical analyses. Its advantage is the fact that it permits the estimation of biomass increments during vegetation. It was subjected to preliminary verification, as far as the research results permitted. As mentioned earlier, the short period of the experiment requires further verification, and at the same the analyses will permit its generalisation to ensure applicability for other energy crops. The results of the study, in the form of developed algorithms, were presented in June 2013 at the 21st European Biomass Conference, Copenhagen, Denmark [Żyromski et al. 2013].

A modified and improved version of the model, permitting running estimations of biomass productivity, was prepared by the research team Szulczewski et al. For presentation on the 5th of October, 2014, at the XII International Science Conference, Brussels, Belgium.

The availability of water for energy crops during their vegetation also has a significant effect on biomass productivity. The field experiment was to provide, among other things, an answer to the question whether it is possible to estimate the limiting effects of water availability and unfavourable weather conditions on the amount of biomass produced. To acquire such information the authors used the results of biometric measurements of plants in the soil evaporimeters and in the canopy of plants surrounding the evaporimeters. The plants in the evaporimeters only had access to water from atmospheric precipitations, while those outside of the evaporimeters could also use the ground waters. The biometric measurements were made on 5 plants for each variant, separately for each of the energy crop species. The measurements permitted the estimation of changes in plant volume at one-week intervals. Whereas, the shoots cot from the plants, due to the fact that their mass was measured, were used for the elaboration of calibration curves of changes in the volume and mass of particular shoots. The number of shoots, in turn, served for the estimation of the volume and mass of individual plants at one-week intervals. The method allowed to demonstrate, in a simple way, the significant correlation between biomass productivity and water availability. Examples of the runs of the volume and mass increments of the test energy plants throughout the entire period of vegetation are presented in Figures 58–61 for the year 2012. For those relations high values of the coefficient of determination were obtained. Comparative analysis of the runs of changes of biomass increments of particular plans demonstrated a notable variation of the effect of water deficit.

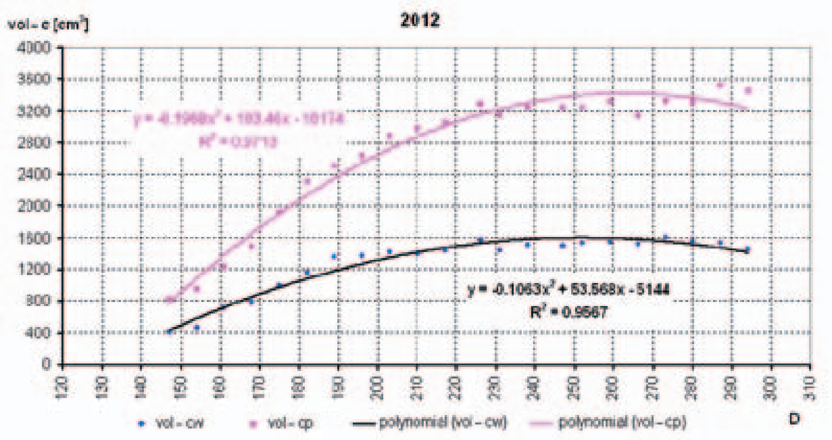


Fig. 58. Volume increments of green mass of aboveground part of single plant of common osier (*Salix viminalis*) in the period of vegetation under conditions of cp – free, and cw – limited access to ground waters, D – consecutive day of the year

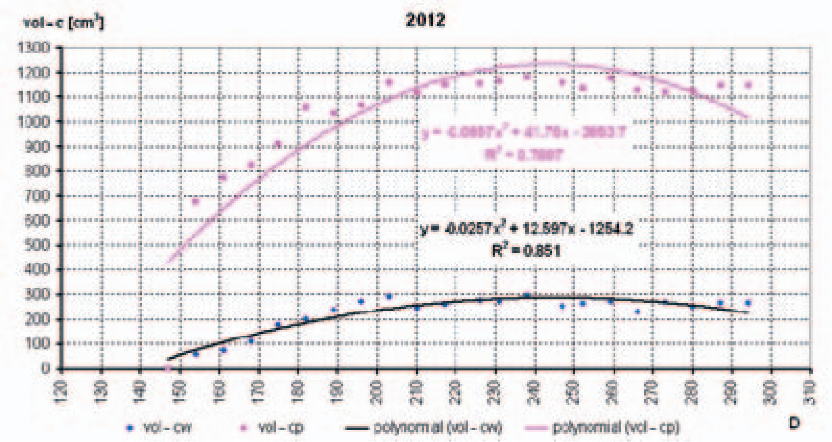


Fig. 59. Volume increments of green mass of aboveground part of single plant of Virginia mallow (*Sida hermafrodita* Rusby) in the period of vegetation under conditions of cp – free, and cw – limited access to ground waters, D – consecutive day of the year

The smallest differences can be observed in the case of common osier (Fig. 58), while both Virginia mallow (Fig. 59) and giant miscanthus (Fig. 60) respond with a distinct decrease of green mass increments in the case of limited access to water.

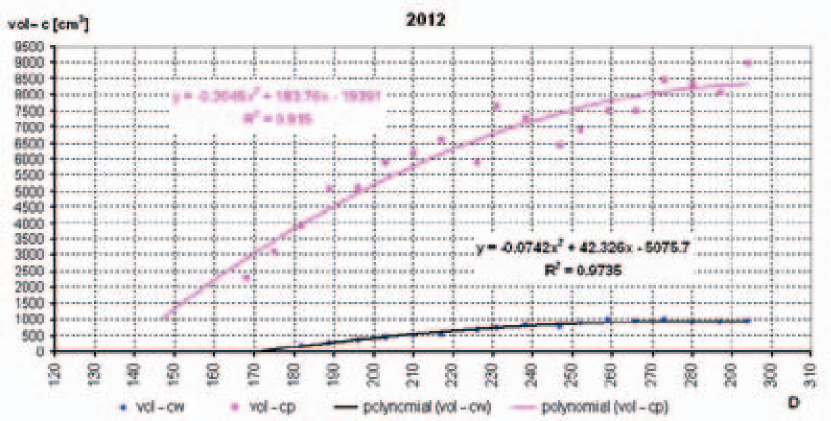


Fig. 60. Volume increments of green mass of aboveground part of single plant of giant miscanthus (*Miscanthus x giganteus*) in the period of vegetation under conditions of cp – free, and cw – limited access to ground waters, D – consecutive day of the year

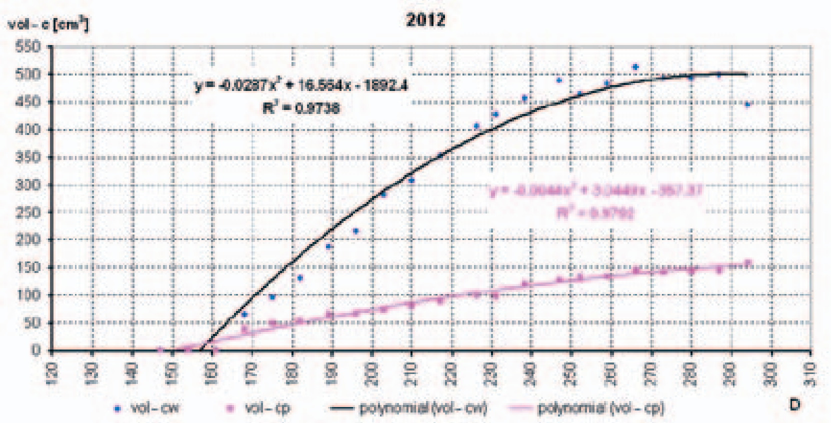
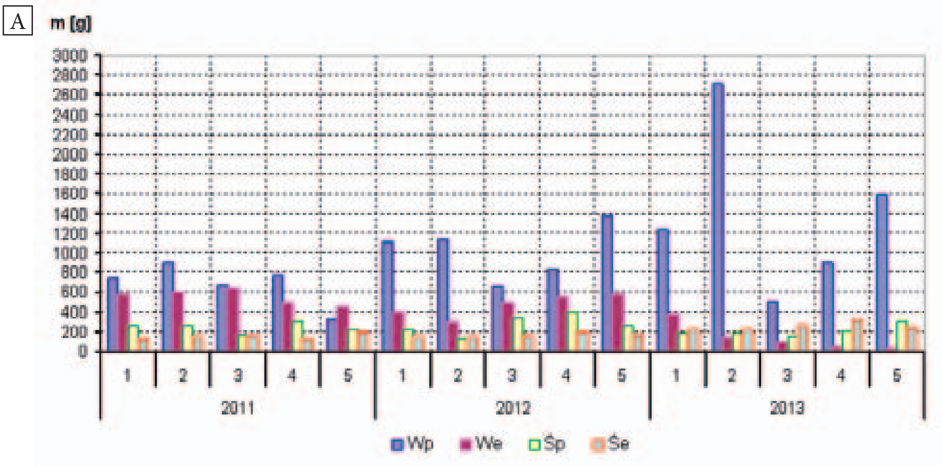


Fig. 61. Volume increments of green mass of aboveground part of single plant of Jerusalem artichoke (*Helianthus tuberosus*) in the period of vegetation under conditions of cp – free, and cw – limited access to ground waters, D – consecutive day of the year

In the course of the biometric measurements it was noted that with limited access to water the plants produce fewer shoots and the shoots have smaller diameters. A different character of biomass increments was observed in the case of Jerusalem artichoke (Fig. 61). The results obtained indicate that this crop plant displays a greater dynamics of increments and produced higher yields under conditions of limited availability of water.

In spite of the short period of the experiment, only three years, an estimation of the final yield of fresh matter obtained from all the energy plants included in the biometric measurements was also made. At the end of each of the vegetation seasons the above-ground parts of the plants were cut off and weighed. The variation of fresh matter obtained from the particular plants is presented in Figures 62a and 63a, while the variation of the mean values for 5 plants of the particular energy crop species in the consecutive years is presented in Figures 62b and 63b.



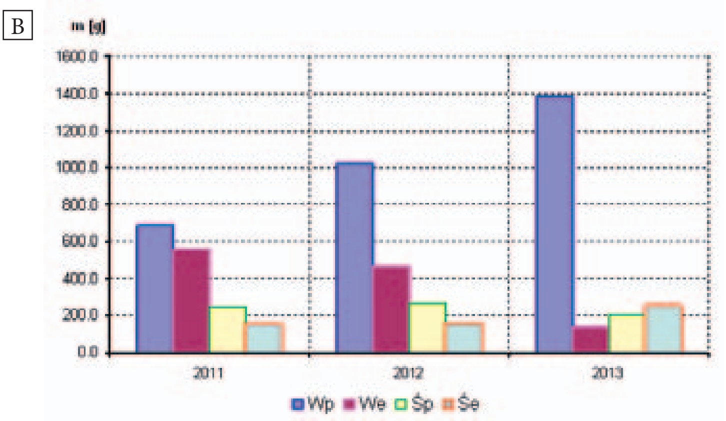


Fig. 62. Mass of the plants at the end of vegetation season
A – single plant: W – common osier (*Salix viminalis*)
and Ś – Virginia mallow (*Sida hermafrodita* Rusby),
(1–5) – evaporimeters number
B – averaged values in the consecutive years of the experiment
Wp and Śp – on a plot, We – Śe – in evaporimeter

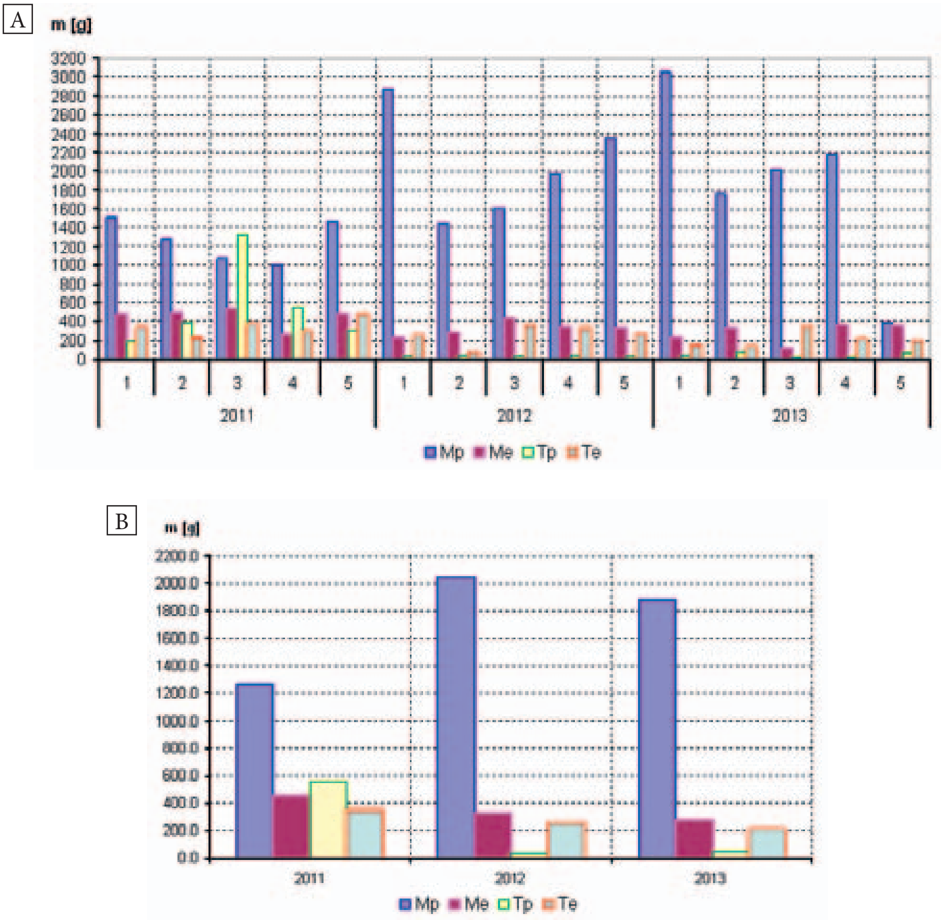


Fig. 63. Mass of the plants at the end of vegetation season
A – single plant: M – giant miscanthus (*Miscanthus x giganteus*)
and T – Jerusalem artichoke (*Helianthus tuberosus*),
(1–5) – evaporimeters number
B – averaged values in the consecutive years of the experiment
Mp and Tp – on a plot, Me – Te – in evaporimeter

A comparative analysis of the yielding of the energy crops was performed also on the example of the year 2013. The analyses and the weekly biometric measurements and observations of the condition of the plants during the period from 18th May to 26th October 2013 permit the conclusion that the lack of possibility of the plants using the ground waters has a varied effect on their condition, which is reflected in the dynamics of their growth during the vegetation period. In May and June 2013 the sums of precipitations of both months together were exceeded by approximately 200 mm. Such a large amount of water could be utilised to the same extent by all of the plants included in the experiment. The the subsequent period high temperatures and long non-rainfall periods resulted in reduced yields of some of the plants growing in the evaporimeters. That related to common osier and giant miscanthus (Phot. 17 and 18), while in the case of Virginia mallow one could note an absence of reaction to such diversified water availability (Phot. 19).

Phot. 17. Yields of control plants of common osier in 2013 growing on a plot (upper row) and in evaporimeters (lower row)

Phot 18. Yields of control plants of giant miscanthus in 2013 growing on a plot (upper row) and in evaporimeters (lower row)

Phot. 19. Yields of control plants of Virginia mallow in 2013 growing on a plot (upper row) and in evaporimeters (lower row)

12. Thermovision (IR) technique and the process of evapotranspiration

Temperature changes of various objects have been the object of research for many years. Temperature is a thermodynamic value characterising the thermal status of a body and determining its ability to transfer heat. One of the methods of contactless measurement of temperature distribution can be the detection of infrared radiation performed by means of an IR camera. Thermographic analyses are based on the detection of electromagnetic radiation emitted by the objects studied in the infrared range, and conversion of that radiation to the visible range. Each body whose temperature is higher than absolute zero emits infrared waves. Thanks to this the distribution of temperatures and their values on the surface of the object studied can be observed [Muzia et al. 2007]. Thermography is the technique of imaging and recording of temperature fields of surfaces of objects studied – temperature at each of their points – thanks to the detection of infrared radiation from those objects. Thermovision or thermography has found a broad application in a variety of fields. At the beginning of the nineteen sixties IR cameras started to be used in the industry, mainly in such branches where temperature determined the correct run of the production process, product quality, or work safety [Adamczewski, Osiadły 2004]. We can enumerate here the metallurgical industry, the chemical industry in the broad sense (refining, petrochemical), glass industry, automotive, aerospace. As a modern method of technical diagnostics of power equipment, it is also used in the generation, transport, distribution and reception of electric power [Szopa, Patschek 2004]. With the use of an IR camera we can detect faults of thermal insulation, both inside and outside of buildings and structures [Adamczewski 2004]. Apart from those areas of non-destructive testing, thermovision has found extensive application in such fields as medicine [Wojaczyńska-Stanek et al. 2004], aviation [Avdelidis et al. 2003] and military technology [Madura 2004]. It also proved useful in tests conducted to establish the originality of works of art and in many other applications [Meola et al. 2004]. Due to the increasing demand and the growing spectrum of applications, the design of IR cameras and measurement systems have undergone a considerable metamorphosis over the last several decades, through improvement of imaging resolution and methods of data processing. An especially significant advance has taken place in the area of the resolution of thermal images, in the design of IR sensors, their kinds, and methods of their cooling [Lubecki 2006].

In spite of the numerous applications enumerated above, the thermovision method of measurement is not free of shortcomings. The IR camera receives not only the IR radiation from the object observed. The camera records also radiation coming from the environment, as well as reflected and scattered from the surface of the object. Both radiation components are attenuated to a degree by the atmosphere on the measurement pathway. Sunlight reflected both from the object and from its surroundings reaches the camera. In addition, in the vicinity of the object measured and the camera there may be other sources of heat radiation that can introduce additional measurement errors. The atmosphere, clouds and the sky also emit infrared radiation. All of those interferences are difficult to estimate [Minikina, Madura 2004].

In spite of those inconveniences, the innovative value inherent in the possibility of acquiring thermal images of objects in the environment is implemented for the study of the variation of processes and phenomena taking place there. Evapotranspiration (ET), as a key element of hydrological balance, is the most difficult factors that has been subjected to quantitative description over the past decades. For the estimation of ET remote sensing tools were applied, with particular emphasis on agricultural areas [Nouri et al. 2013]. Those authors admit in their report that the quantification of evapotranspiration from areas with mixed landscape is still complicated and difficult due to the diversity of plant species, degree of land cover, microclimate, and also due to the costly methodological requirements. Based on their knowledge of agriculture and forestry, they point out the advantages and disadvantages of ET estimation based on remote sensing. Nevertheless, studies were conducted concerning the construction of algorithms for the mapping of evapotranspiration (ET) of grasslands with the use of local weather information and high-resolution IR images acquired by means of a FLIR camera with resolution of 320 x 240 pixels, mounted on a helicopter [Steven 2005]. The realization of the task included the use of meteorological data that permitted the calculation of ET at 15-minute intervals and 24-hour period estimates in conjunction with IR measurements. The combination of estimated ET data and IR images served for the acquisition of information on water consumption by the grassland vegetation. In total, 69 measurements were used in that experiment for the estimation of ET on 5 representative plots situated within the research area.

The IR technique was applied also by Spanish researchers for the detection of the effect of water stress in relation to the quality of fruits in orchards. IR images were acquired by means of a drone (UAV), on which a 6-band multi-spectral camera was installed, MCA-6, Tetracam Inc., California, USA [Suárez et al. 2010]. The drone performed flights over selected orchards in the summer of 2008, at an altitude of 150 m above ground level. In the course of the experiment a series of 12 images were made, at various times, above two research centres, and eleven above a commercial field planted with experimental nectarines and peaches. The photos were made in a period starting from the beginning of the 2nd phase of fruit growth, i.e. from 12th June, to the end of the harvest, i.e. to 21st August. A study on the water stress of peaches at various levels of soil moisture was conducted also by a research team from Romania and Turkey [Septar et al. 2014]. That research, as reported by the authors, was conducted due to the fact that the achievement of high quality of peach fruit depends on the maintenance of water stress, from mild to moderate, in the cultivations during the vegetation period.

Research concerning water stress, but this time of seeds of broad bean (*Vicia faba* L.), was conducted in a greenhouse at the Scottish Crop Research Institute, Invergowrie, Scotland [Leinonen, Jones 2004]. During the experiment 2 groups of plants were subjected to drought stress. The drought treatments were performed separately for each of the experimental groups, while a control group of seedlings was watered daily. IR and conventional photographs were made for ten plants from each group. The IT images were taken separately, using a tripod-mounted camera. Research conducted with the use of the IR technique in agricultural experiments has been presented in a highly abbreviated form. However, in the course of its realization no universal or versatile methodology has been developed that could be applied in other studies. The scope of the research was determined by the requirements and by the measurement equipment available.

It is also necessary to mention about the polish scientists research on the estimation of evapotranspiration and plant water stress on the basis of temperature measurements with IR by Łabędzki [1995, 1996, 1997] and Baranowski at al. [2005].

Notably more numerous application of thermovision can be found in the literature concerning the energy surveys or audits of objects. The demand for such knowledge contributed significantly to the reduction of the cost of IR cameras and to their greater availability.

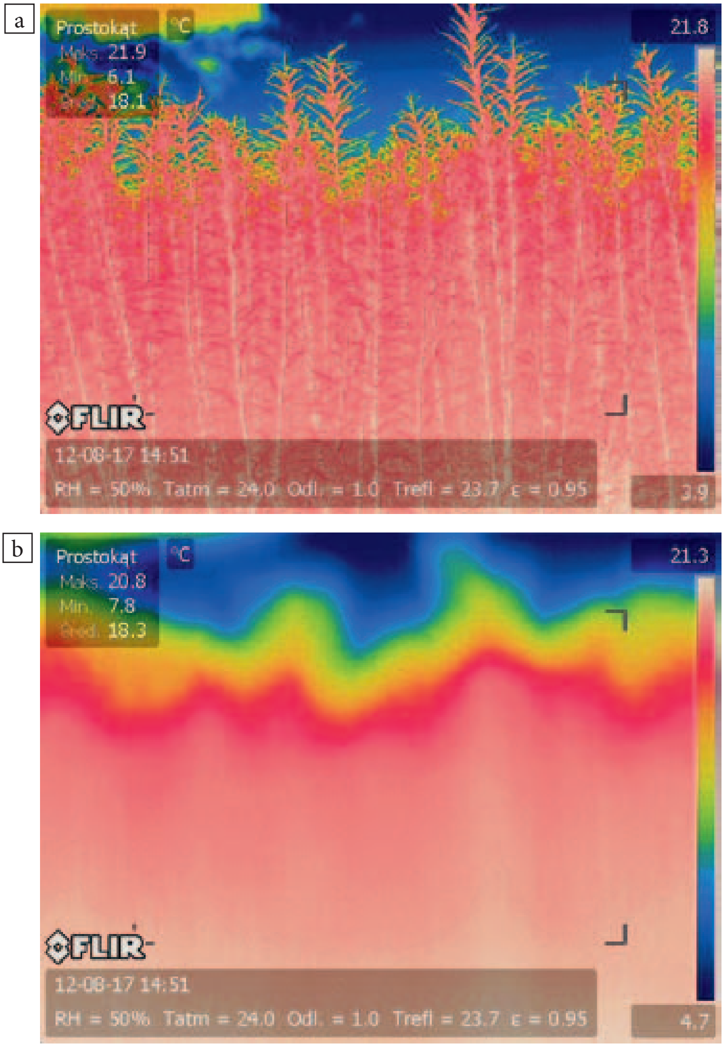
Independently from the results of the field experiment presented in this monograph, concerning the evapotranspiration of four energy crops (common osier, Virginia mallow, giant miscanthus and Jerusalem artichoke), and their interpretation, the authors decided also to present their own results of an estimation of the degree to which the IR technique can be applied for the imaging of the variation of the intensity of evapotranspiration of the energy crops in relation to their access to water. In the situation of addressing a totally new problem, it was also decided to develop an original methodology of measurement and of interpretation of results obtained from field experiments. The methodology is different as in the field experiments including the use of the IR technique, encountered so far in the literature and discussed earlier, the IR images were taken from above plant-covered areas. Whereas, in the experiment in question the images were taken from a single point situated opposite a canopy of energy plants. For the purpose of thermal imaging of the variation of evapotranspiration of the energy crops in relation to water availability for the plants in the years 2011, 2012 and 2013, series of IR images were made for all four energy crop species with the use of an IF camera type "FLIR 600 series" which permits taking images with resolution of 640 x 480 pixels. The camera permits the acquisition of full-colour photographs in the visible light (Phot. 20 and 22) as well as complete IR images in a selected colour scale (Phot. 21, 23 and 24) [Instrukcja obsługi do kamery termowizyjnej... 2009]. For accurate measurement of temperature, it is necessary to compensate for the effect of various sources of radiation. This is done automatically by the camera, after entering specific parameters of the object:

- Emissivity of the object,
- Ambient temperature (reflected apparent temperature),
- Distance between the object and the camera,
- Relative humidity,
- Temperature of the atmosphere.

For the measurements to be precise, the object parameters must be set. That can be done locally or globally. For example, it is recommended that the distance to the object is not greater than 9 m. According to the Manual of the IR camera that we used, at a distance of 7–8 m the measurement should be correct. As at the time of taking the IR images the distance to the canopy of common osier was somewhat greater than 8 m, but did not exceed 9 m, the measurements should be considered as performed correctly. The measurement site was marked and the distance was maintained at all measurements made in the consecutive years of the experiment. As concerns the emissivity, the User Manual of the camera specifies that the materials of the objects and their processed surfaces are characterised by emissivity in the range from 0.1 to 0.95. The Manual provides a Table of emissivity values containing a large spectrum of those values for a variety of materials and surfaces, which largely facilitates the work of the user. However, if the user wants to avoid measurement errors and is not sure what values what values should be used, he can apply values recommended by the manufacturer, and then the values to be used are as follows: emissivity 0.95, distance 1.0 m, ambient temperature (reflected apparent temperature) + 20°C, air temperature +20°C, and relative humidity 50%. In the course of the IR measurements the authors made use of those recommendations.

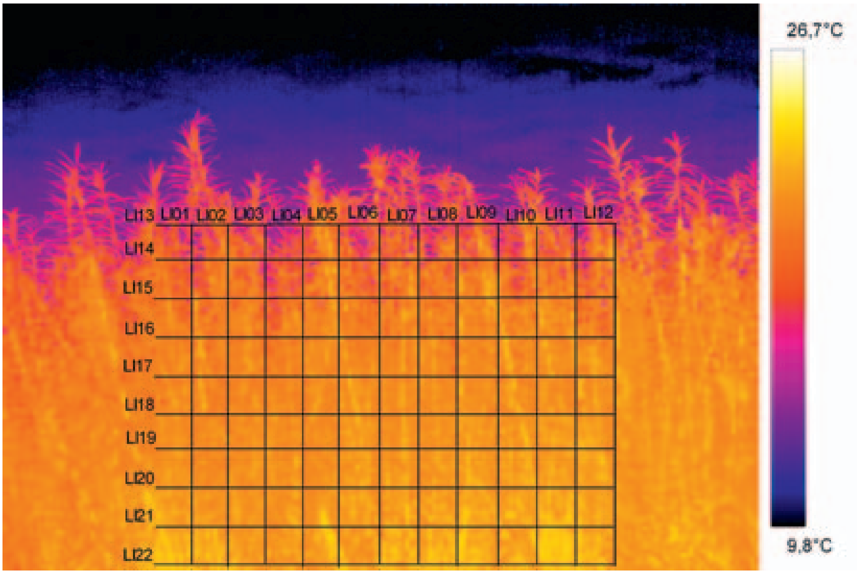
In total, during the three years of the study, over 1400 true photographs and IR images were taken. However, in the course of the realization of the task the problem proved to be more complex. The lack of procedures and methodology, both concerning the measurements and the interpretation of results for the purpose of identification of the relations of both processes, posed the necessity of developing our own methodology for one of the energy crops, i.e. common osier. The authors arrived at the conclusion that the development of a methodology for one of the plant species will permit its adaptation for the other species. Due to the high variation of IR images in time, in the first year they were taken at variable time intervals, from 1 to 5 minutes. However, the experience acquired in the course of the experiment led to the conclusion that the adoption of a longer time interval between the individual IR images will be the most justified. For that reason in the following years the adopted rule was that images were taken every 10 minutes during the period from 10:00 to 16:00. Another important factor was the recommendations given in the User Manual [Instrukcja obsługi do kamery termowizyjnej... 2009] which specify that IR measurements should be taken under conditions of stabilised fair weather. Rain and snow have also a cooling effect on the electric elements of the camera system. IR measurements can be conducted with satisfactory results at slight snowfall (dry snow) or at a slight drizzle, whereas, the quality of IR images deteriorates under conditions of heavy snowfall or rainfall and then it becomes impossible to obtain reliable measurement results. The primary cause of that is the fact that intense snowfall or rainfall are impermeable to infrared radiation and then the measurement taken relates rather to the temperature of the snow or the rain drops. Those recommendations were one of the limiting factors in the process of acquisition of IR measurements of the canopy of common osier. Due to the fact that the measurements of field evaporation of energy crops in the evaporimeters were made twice a day, i.e. in the morning and in the evening, there was no possibility of direct determination of correlations between the results read from the IR images and the values of evapotranspiration obtained from the soil evaporimetrers. However, our studies on evaporation conducted so far and the measurement capabilities of the Wild EWP 992 evaporimeter used in the field experiment permitted its programming as to the time of recording evaporation from open water surface. In the first year of the experiment the recording of evaporation was adapted to the times of taking the IR images. The use of the device permitted the acquisition of values of evaporation from open water surface. That in turn allowed indirect estimation based on the results of evapotranspiration of common osier obtained during 24 hours. The method applied is the only one among those currently available, as in spite of the abundance of formulae for the estimation of evaporation from open water surface none of them permits credible calculations for time periods shorter than one day. Our analyses demonstrated that the colour spectra recorded in IR images are subject to notably more frequent changes than the dynamics of evaporation recorded by the Wild evaporimeter EWP 992. For this reason, in the years 2012 and 2013 that device was reprogrammed so that the values of current evaporation from open water surface were recorded at 10-minute intervals. To facilitate the interpretation of the IR images obtained, they were taken under conditions of stable weather, at 10-minute intervals. The material acquired consisted of series of natural photographs and IR images, sharp and diffuse. The processing of the materials obtained in the sharp and diffuse images from the IR camera was performed by means of the program FLIR Researcher 2.9 Pro, supplied with the measurement equipment. Photographs with true images ascribed to a specific time can be correlated with distributions of temperature values in infrared images and with the height of plants of common osier on the day of the measurements, based on the results of the biometric measurements. The application of that software package for the processing of sharp images and diffuse images permitted the superimposition of a grid of vertical and horizontal sections (Phot. 23 and 24). The diffuse images permitted distinct delineation of thermally active zones. The spatial variation of temperature obtained from the particular infrared images permitted the generation of strings of temperature values for the consecutive sections and, subsequently, for the construction of the runs of their variation during a measurement day, examples of which are presented in Figures 64 and 65.

Phot. 20. True photograph of canopy of common osier

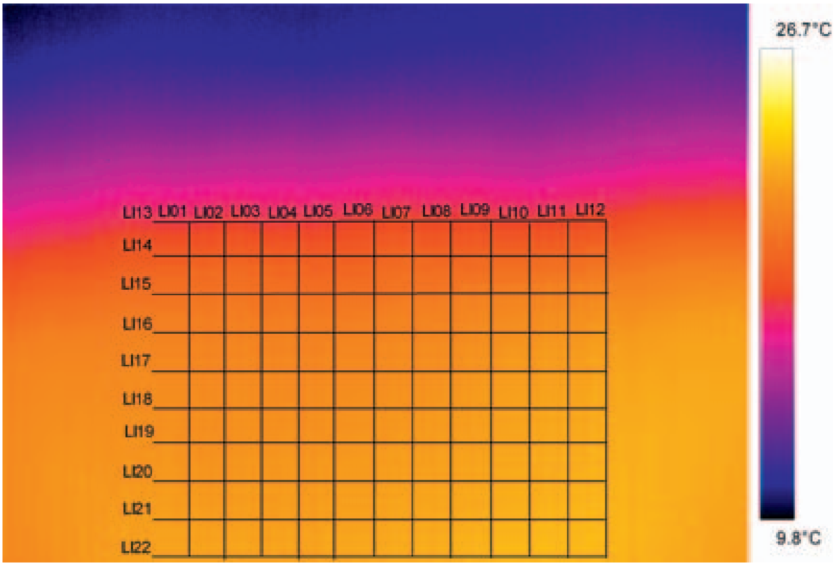


Phot. 21. IR image of canopy of common osier:
A – sharp, B – diffuse, with listing of parameters measured

Phot. 22. True photograph of canopy of common osier
from 31st August, 2013, 11.04 hrs – photo No. 5232



Phot. 23. IR image from 31st August, 2013, 11.04 hrs
with superimposed section grid – photo No. 5207



Phot. 24. Diffuse IR image from 31st August, 2013, 11.04 hrs
with superimposed section grid – photo No. 5207

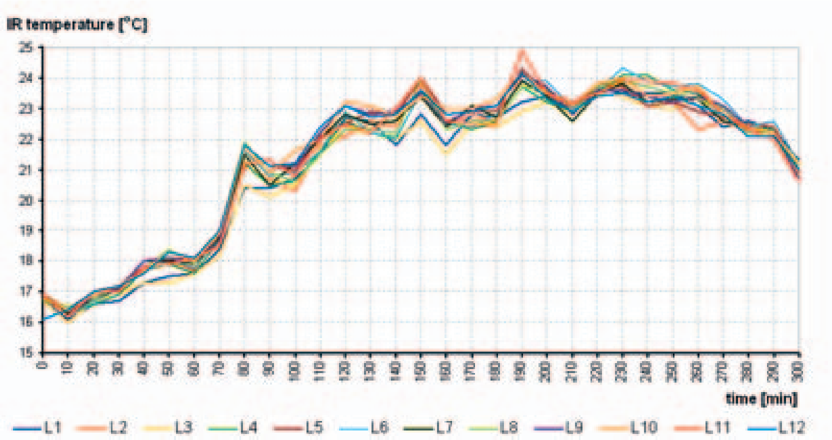


Fig. 64. Runs of temperature distributions from IR image vertical sections L1–L12
on 31st August, 2013

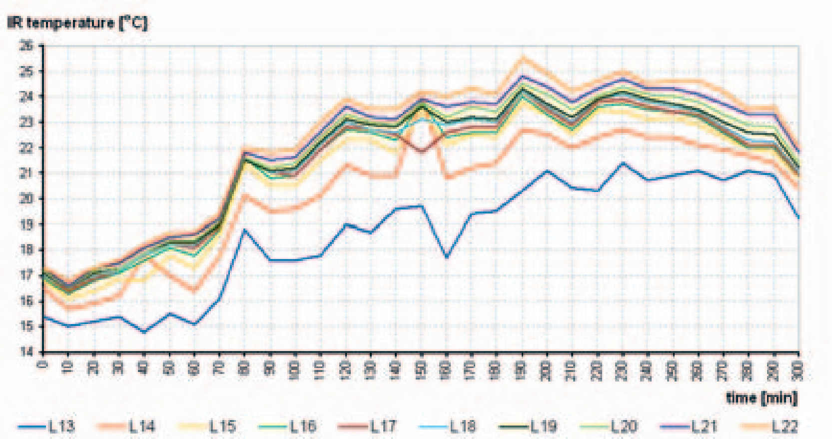


Fig. 65. Runs of temperature distributions from IR image horizontal sections L13–L22 on 31st August, 2013

The next stage in the processing of the results obtained was the determination of correlation between the temperature values and the sums of evaporation from open water surface. The values obtained are assigned to periods between the times of taking individual photographs in the course of a measurement day. The highest coefficients of determination obtained for the particular sets corresponding to the successive times of measurement permitted the determination of a kind of coordinates that provide the best description of the correlation of temperature values from the IR images with the sum of index evaporation (Fig. 66 and 67).

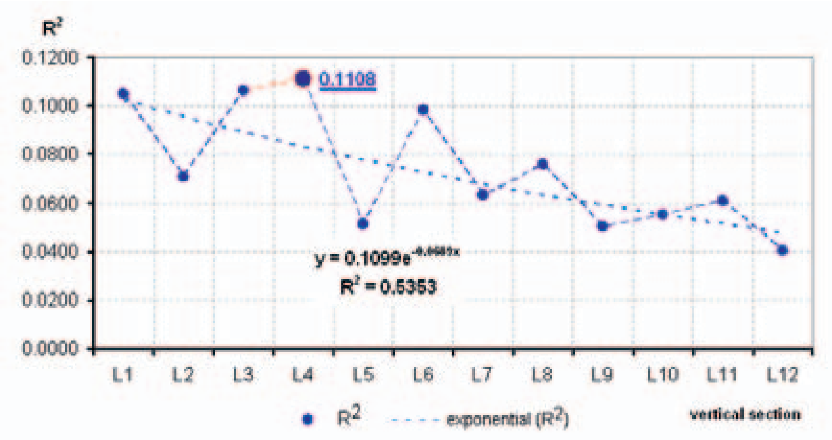


Fig. 66. Variation of coefficients of determination R^2 for correlation between evaporation from open water surface measured with Wild evaporimeter EWP – 992 and temperatures in IR image vertical sections L1–L12 on 31st August, 2013

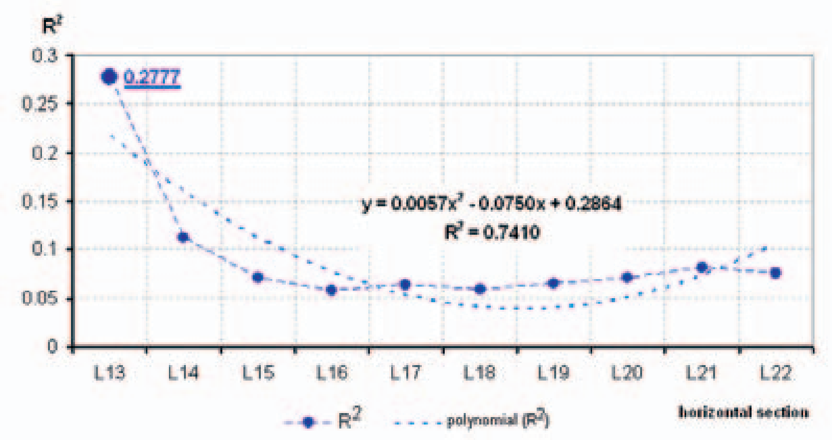
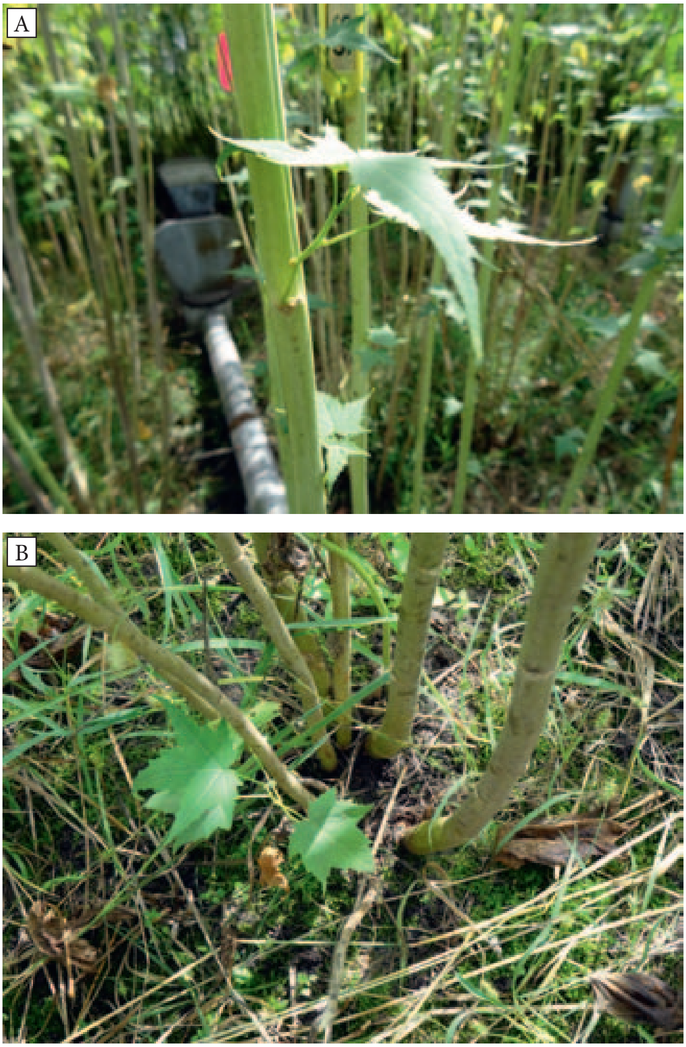


Fig. 67. Variation of coefficients of determination R^2 for correlation between evaporation from open water surface measured with Wild evaporimeter EWP – 992 and temperatures in IR image horizontal sections L13–L22 on 31st August, 2013

The method is labour-consuming, as it requires the application of the procedure described above for every measurement day. An important element is the difficulty in correlating the values of thermal distributions with evaporation obtained with the method of field water consumption (PZW). The PZW method requires either daily irrigations or extended periods of balance, which does not allow the estimation of evaporation changes for time periods shorter than 24 hours. It is, however, a certain proposal of capturing the variation of the dynamics of evaporation, in this case for common osier, for limited access to water in the case of correlating the results obtained with evaporation measured by means of soil evaporimeters. The analyses, as well as the observations made in the course of the study, indicate the justifiability of estimation of emissivity in the course of the period of plant vegetation. A change in the colouring of plant surface and the weather during a day (clear or cloudy) may be factors significantly affecting the thermal structure of plant canopy. A verification of the method applied can be performed after a greater number of measurements and over a longer period of time. The confrontation of results obtained from those from soil evaporimeters will permit an assessment of their credibility.

13. Observations and comments on the field experiment

The field experiment, the analyses performed and the observations made in the course of the field experiment permitted the authors achieve a closer understanding of the problems related with the growth and development of the four energy crops selected for the study, and with their response to the environmental conditions. Whereas, the agrometeorological observations and measurements provided a background for the conditions under which the plants grew and developed. The fact of starting the experiment with annual plants and its second part with biennial plants permitted preliminary quantification of the environmental determinants. The acquisition of the greatest possible amount of information on changes of atmospheric factors characterising the thermal and precipitation conditions and the migration of ground waters resulted in acquiring information on the possibilities of replenishment of soil water resources. Whereas, the simultaneous monitoring of the state of soil moisture in the soil evaporimeters and over the surrounding areas permitted the obtainment of precise information on the current water resources under the energy crop plants under study. Those factors, analysed comprehensively during the vegetation periods in the consecutive years of the study and in relation to the development stages of the particular plant species, permitted the estimation of their growth dynamics and value of evapotranspiration. In view of the fact that the plots with all of the plants were situated next to one another, all of the agrometeorological factors could be treated as an element which had the same physical status in relation to each of them. The biometric observations conducted in short time intervals, every week, created the possibility of comparative analyses of growth dynamics among all of the plants. Irrespective of the parameters measured, due to the high frequency of the biometric measurements we could observe the natural adaptation abilities of the particular plants with respect to the possibilities of using the available water. Among the four plant species included in the study, the greatest possibilities and even an ability of adaptation to the variable weather conditions in the particular years could be noted observing Virginia mallow. In periods of water deficit – extended non-rainfall periods – manifested in a reduction of water resources in the soil profile and, consequently, lowering groundwater table, which was indicated by the devices monitoring those agrometeorological factors, that plant inhibited its growth and development by shedding leaves and, in the next step, auto-elimination of the weakest shoots. However, in a situation when the conditions of water availability improved, in spite of the nearing end of the vegetation period the plant produced new leaves and started to grow new shoots (Phot. 25A and 25B). In turn, an excess of water in the soil and, consequently, its stagnation on the ground surface, initially notably inhibited the dynamics of plant growth and contributed to a discolouration of leaf surface, which can be seen on the example of common osier (Phot. 26).



Phot. 25. Plant regeneration after a period of water deficit – Virginia mallow on 31st August, 2014
A – growth of new leaves in the place of old ones, B – growth of new shoots

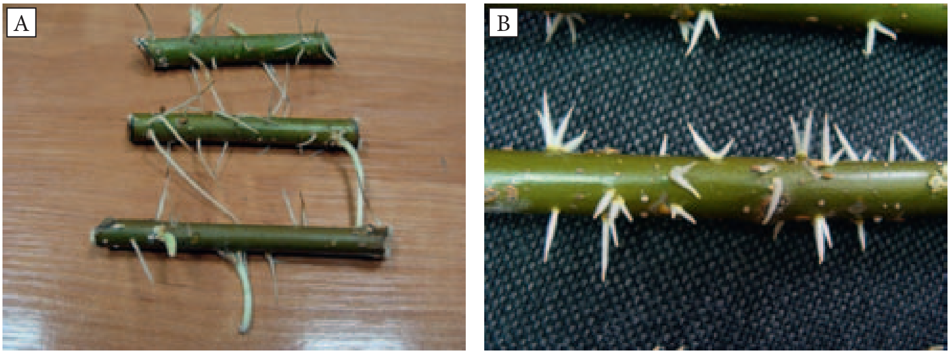
Phot. 26. Growth inhibition and changes in leaf colouring of common osier
as a result of flooding on 7th May, 2013

The observations conducted in the years 2011, 2012 and 2013 revealed that the vegetation of the energy crops included in the experiment (common osier, Virginia mallow, giant miscanthus and Jerusalem artichoke) began in April, with varied dynamics. The plants, due to their small size at that time and the low air temperature, used mainly the soil water accumulated during the winter period. It was only May, with higher air temperatures, that conducive to their accelerated growth, which led to faster exhaustion of soil water resources and caused the drying of soil surface. During that period those resources could be replenished primarily by atmospheric precipitation. For this reason an estimation was made of the potential possibilities of rainfall water use by the energy plants in the period from May to October. That approach is significant in that the information provided in research literature on the water requirements of energy crops is, in the light of our studies and observation, imprecise and even overestimated. That problem is a very broad one, and still open, and involves numerous factors for which it needs to be decided which of them and in what situation constitute water deficit. In our opinion there is an interesting publication, frequently cited in research reports and in the world scientific literature, and concerning the problems of water deficits and describing them over a notably broader range than is the case in our monograph [Rijsberman 2006]. In spite of the short – only three years – period of our experiment, the analyses of diurnal sums of precipitation and of the frequency of their occurrence permitted also a more precise determination of the potential and actual possibility of rainwater utilisation by the studied energy plants in the period of vegetation. In the first year of the experiment – 2011 – in the period from May to October, i.e. in the summer half-year, the sum of precipitations was 453.8 mm. Whereas, in the period from May till September high diurnal sums above 15 mm$\cdot$day^{-1} were noted 10 times. On two occasions the sums were higher than 30.0 mm$\cdot$day^{-1}. Somewhat lower values, within the range from 12.1 to 14.5 mm·day^{-1}, were noted three times. In total, the sum of precipitations in 2011 from only the high diurnal sums amounted to 283.7 mm. In 2012 the sum of precipitations for the summer half-year was 427.6 mm, and thus it was somewhat lower than in the preceding year. In that period we noted 8 days with diurnal sums above 15 mm·day^{-1}, and 4 with diurnal values in the range from 11.0 to 13.3 mm. The sum of precipitations from only the high diurnal sums amounted to 255.7 mm, i.e. not much less than in the preceding year. The year 2013, in turn, was decidedly different, as the sum of precipitations for the summer half-year amounted to 541.3 mm, being considerably higher than in the preceding two years. That year was also richer in the number of days with precipitations exceeding the value of 15 mm·day^{-1}. The total number of such days was 14. On four days the diurnal sums were notable, at 48.2, 38.0 and twice 35.6 mm during a day. As in the preceding years, in the class of atmospheric precipitations above 10 mm/day the sums fell within the range from 10.1 to 12.2 mm and there were 4 such days. Taking into account the entire sum of atmospheric precipitations, consisting of only the highest diurnal values, it amounted to 410.5 mm. Relative to the sums of atmospheric precipitations from the summer half-years, the sums of precipitations composed of the extreme values discussed above constituted, in the consecutive years, 62.5, 59.8 and 75.8%, respectively. They were considerable, but it can be stated with a high probability that the energy plants in the field experiment could make use of them only to a small degree. For this reason we should take into account two possible variants that took place in the course of the field experiment. It is a fact that the field water capacity of the soil profile limits the possibility of plants' making use of ground water, which results from the retention properties of the soil. During the occurrence of high sums of atmospheric precipitations, in the case of soil evaporimeters excess rainwater can be accumulated on the surface of the pots and gradually be transformed into runoff. That process, in the case of sandy-loamy soils such as those in the territory of the Agro- and Hydrometeorology Observatory Wrocław-Swojec, proceeds relatively rapidly, which means that the effectiveness of high diurnal sums of precipitations is very low. Whereas, in the case of plots, excess rainfall water was transformed into surface runoff. This information is an effect of our observations that we made in the course of the field experiment. It was also used for conducting simple simulation analyses which were performed on the basis of the total amounts of precipitations in the summer half-year periods in the particular years of the experiment. And thus, assuming that the lowest effectiveness is characteristic of diurnal sums of precipitation above 15 mm·day^{-1}, it was decided to perform a correction of the rainfall which, according to our estimates, could be used by the energy plants. For this purpose the sums of precipitations for the whole summer half-year were reduced by 50% of the sums from the extreme diurnal sums. In the consecutive years of the experiment that gave the values of 331.4 mm in 2011, 323.5 mm in 2012 and 359.3 mm in 2013, respectively. The experiment was concerned with the extensive cultivation of energy crops.

Phot. 27. Variation in the possibility of penetration of atmospheric precipitation through the crowns of energy plants on 2nd of August, 2014
A – Virginia mallow, B – common osier, C – giant miscanthus, D – Jerusalem artichoke

The values of the sums of precipitations obtained from the calculations appear to be low, but the biometric measurements conducted in the course of the field experiment indicated only a reduction of yields under conditions of limited availability of water, which was the case in the soil evaporimeters, but did not make the cultivation of the plants impossible. Another highly important factor which undoubtedly permitted the retention of precipitation waters on the crowns of the energy plants were the dynamically changing conditions of interception of the plants under study. This resulted from the fact of changes in the degree of soil surface coverage by the plants in the course of vegetation (Phot. 27). The shapes of the leaves and the manner of their attachment to the stems facilitated the movement of rainwater to the plant roots to a varying degree. The observations made in this respect by the authors permit the conclusions that giant miscanthus performed the best in terms of rainwater accumulation on the leaves and its transfer to the soil surface. In the case of that plant the assumption that it can make use of only 50% of precipitation water should most probably be corrected up. However, more accurate information in this regard can only be acquired after conducting an at least several-year study on the interception of the energy plants.

In the course of the field experiment an attempt was also made at finding out, on the example of common osier, at what time the preparation of new seedlings for planting should be started. For that purpose short shoots with length of about 10–15 cm were isolated from daylight and atmospheric air. The experiment was conducted in a number of periods. After about three weeks the condition of the potential seedlings was examined at every time it was found that they had well-developed root systems, permitting the use of the shoots for planting, which permits an acceleration of their vegetation (Phot. 28). The experience acquired in this way permits the conclusion that a notably greater amount of planting material, with uniform parameters, can be produced. However, the knowledge acquired requires verification in field conditions, to determine whether the seedlings produced in that manner have the same viability as those produced in the classic form.



Phot. 28. Seedlings of common osier after application of growth acceleration
Effects after two weeks: A – 12th February, 2013, B – 19th April, 2013

14. Summary and conclusions

The methodology proposed, the field study conducted in the years 2011–2013, and the analyses of the accumulated and processed research material permit the formulation of preliminary general conclusions. This reservation results from the fact that the three-year period of the field experiment is too short for the formulation of too far-reaching conclusions. However, the varied weather conditions in the particular years of the study permitted the observation of certain regularities concerning the evapotranspiration of common osier, Virginia mallow, giant miscanthus and Jerusalem artichoke under conditions of varied access to water. Whereas, the various techniques applied for the interpretation of the results obtained justify the conclusions that the authors decided to present in this part of the monograph.

1. The measurement method applied in the study and the results of field experiment obtained on the basis of its use permitted the development of the model WSMT concerning the evapotranspiration of four energy plant species. The model permits the determination of the moving average of the value of actual evapotranspiration on the consecutive days of the vegetation period on the basis of atmospheric precipitation and evaporation from open water surface, measured with evaporimeter EWP 992, or value of reference evapotranspiration calculated with the formula developed by Penman–Monteith.
2. Since the Penman–Monteith method is accepted in the world literature as a reference method, the tool developed in the study, in the form of the software program “EVAPO”, permits easy calculation of reference evapotranspiration necessary for the variant determination of evapotranspiration of the energy crops discussed in this work.
3. The application of a uniform model for the estimation of evapotranspiration of the plants studied permitted an evaluation of the variation of their evapotranspiration, both among the particular plant species and in the individual years of the experiment. The acquired observations and experience, and the verification of the model, indicate the justifiability of selection of its parameters and its good fit to the values obtained from field measurements.
4. The uniform TDR method of soil moisture measurement under conditions of its varied accessibility for plants (experimental plots where the plants could use both ground water and atmospheric precipitation waters, and soil evaporimeters – possibility of using rainfall water alone) indicates only slight differences in the two var-

iants, under the condition that it is applied for the determination of the balance of water used by the energy plants over longer time intervals, e.g. a week or a decade.

5. The study indicates the possibility of using simple statistical models for the estimation of evapotranspiration of energy crops on the basis of selected measured or calculated agrometeorological elements. That parameter can be estimated with a high accuracy using e.g. diurnal sums of reference evapotranspiration determined with the Penman–Monteith method, cumulated during the vegetation period, and diurnal sums of air temperature, cumulated in the same manner. Poorer results are obtained with the use of direct correlations for the diurnal values. The extension of the summing periods to a pentade, a week or a decade notably improves the quality of the results obtained.
6. The proposed empirical coefficients developed for common osier, Virginia mallow, giant miscanthus and Jerusalem artichoke permit the estimation of evapotranspiration of those plants for various time intervals, such as a week or a decade. The form in which they were developed allows their use in the same way as the coefficients applied so far in the literature concerning crop plants.
7. Notable variation in the effect of water deficit on biomass productivity under conditions of extensive cultivation of energy crops is observed. The most sensitive to water deficit were giant miscanthus and common osier. That those species should not be grown on sites with deep lying ground water table, to which the plants have no access. Virginia Mallow has considerable adaptation abilities in this regard. Jerusalem artichoke proved to be the least sensitive to water deficit.
8. The pilot study with the use of the IR technique for the estimation of evapotranspiration of common osier supported the hypothesis of the authors concerning the possibility of determination of that parameter with an indirect method, based on the use of IR images and measurements of evaporation from open water surface. That technique permits the determination of thermally active zones within the canopy of energy plants. However, it is also burdened with notable limitations due to weather conditions unfavourable for taking IR images, and to the considerable dynamics of thermal changes during the day. That is not reflected in the dynamics of evaporation from open water surface.
9. The field determinations of evapotranspiration and field water consumption conducted for common osier, Virginia Mallow, giant miscanthus and Jerusalem artichoke under conditions of varied access to water permitted the verification of their water requirements in the form of values of atmospheric precipitation, specified in the literature, that should be available for the plants during the period of their vegetation. However, the results obtained need further validation on the basis of independent material from consecutive years and from other regions of cultivation. A longer period of study will allow the estimation of the time period required for stabilisation of biomass increments and for water management by the plants.

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